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Nonlinear discrete-time multirate adaptive control of non-linear vibrations of smart beams

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ABSTRACT

The nonlinear adaptive digital control of a smart piezoelectric beam is considered. It is shown that in the case of a sampled-data context, a multirate control strategy provides an appropriate framework in order to achieve vibration regulation, ensuring the stability of the whole control system. Under parametric uncertainties in the model parameters (damping ratios, frequencies, levels of non linearities and cross coupling, control input parameters), the scheme is completed with an adaptation law deduced from hyperstability concepts. This results in the asymptotic satisfaction of the control objectives at the sampling instants. Simulation results are presented.

1. Introduction

Active vibration control of flexible structures has been attracting much attention in aerospace engineering, civil and mechanical engineering for over three decades [1–4]. Owing to their good characteristics of high actuating performance, lightweight and electromechanical coupling effects, piezoelectric sensors and actuators have been increasingly applied in vibration control of structures. The control strategy plays a crucial role in these structures, especially in the lightweight ones. Thus, many control strategies have been applied to piezoelectric actuators, such as velocity feedback [5], neural networks [6], adaptive control [7], fuzzy control [8–10] positive position feedback control [11].

Most of the research on vibration control of structures with piezoelectric actuators is based on linear models. We summarize hereafter the limited work available in the literature on nonlinear vibration control of smart piezoelectric structures.

Oueini et al. [12] introduce an algorithm based on cubic velocity feedback for the first time in controlling a nonlinear vertically excited beam. They analyzed the bifurcations in the simulation and experimental results.

The effect of the piezoelectrically induced stress stiffening on the dynamic instability of a laminated composite beam using PZT layers has been investigated in Ref. [13]. A simple negative velocity feedback control algorithm that couples the direct and converse piezoelectric effects was employed to actively control the dynamic response of the beam through a closed control loop. The influence of the feedback control gain on the response of the beam was also evaluated.

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In Ref. [14], the proportional and derivative potential feedback control strategies are used to study the nonlinear vibrations of piezoelectric/elastic/piezoelectric sandwich beams. The harmonic balance method and one mode Galerkin approximation in space were adopted. The feedback effects are analyzed for small and large vibration amplitudes of sandwich beams. The frequency response curves are presented and discussed for various gain parameters.

The robust vibration control of a nonlinear plate using piezoelectric actuator was investigated in Ref. [15]. Based on a sliding mode controller, a fuzzy system was introduced first, in order to mimic an ideal controller. Next, a robust controller was designed based on the compensation of the difference between the fuzzy controller and the ideal one.

A robust optimization approach based on smart materials has been presented in Ref. [16] for suppressing the vibration of Euler–Bernoulli beams. A fuzzy controller has been desirably arranged in the piezoelectric actuator/sensor loop to reduce the forced vibrations for any arbitrary stimulation. The Bee Algorithm has been selected to optimally tune the piezoelectric patch values according to the industrial catalogue, and also to figure out the optimum location of these patches on beams.

In Ref. [17], a robust adaptive control system was derived for the attitude tracking and vibration suppression of an orbiting spacecraft with flexible appendages bonded with piezoelectric actuators/sensors. The problem of spacecraft attitude control and the elastic vibration suppression problem were treated separately. Two controllers were designed for the attitude tracking subsystem based on sliding mode control techniques. For actively damping the elastic motion, a vibration compensator was separately designed based on a modal velocity feedback control method to determine the control voltage of piezoelectric actuators.

The aforementioned research works are based on continuous-time schemes. However, due to recent developments of the computer and interface hardware, digital controllers are utilized for controlling almost all mechanical systems such as robots, motors, machine tools, and hard disk drives, because of cost, reliability, flexibility and compactness. The approach most frequently pursued for digital implementation is the Continuous Time Design (CTD), or emulation, which consists in computing a continuous-time control law at the sampling instants, based on state or output samples, and applying it, constant during the sampling period, through a zero-order holder device. However, CDT fails when the sampling period cannot be sufficiently reduced, leading to a loss of properties and performance that were assured in continuous-time or even to instability. In order to account for digital implementation during the design step, a nonlinear sampled-data controller design framework is needed [18]. This Sampled-Data Design (SDD) approach for designing ad-hoc sampled-data controllers by taking sampling into consideration from the beginning in the design process, is based on the Exact Sampled Representation (ESR) [19]. The ESR is a model of difference equations equivalent to the continuous dynamics at the sampling instants, which represents the link between the input of the holder device and the sampled measures of the plant. Besides the ESR, in order to satisfy control objectives in a discrete context (stabilization or tracking at the sampling instants, dead beat or minimum time responses), multirate sampled-data techniques have been recognized as an effective means. In this case, the control variables are still calculated on the basis of the measures at the sampling instants, but are kept piecewise constant over fractions of the sampling period. These multiple changes of the control variables in the inter-sampling interval, produce an increased number of degrees of freedom, needed to satisfy the control objectives in the discrete setting. In order to obtain the ESR of a nonlinear continuous system under normal (zero-order holder) or generalized (multirate) sampling procedures, a formalism based on infinite asymptotic series expansions is used [20]. The solutions obtained are thus also in general described by their asymptotic expansions in powers of the sampling period, but in practice it is sufficient to consider only a finite number of terms to get efficient solutions, corresponding to the truncation of the infinite series expansion of the digital solution at a fixed order. For certain classes of systems, an appealing situation occurs, where the ESR series is finitely computable under a diffeomorphism and/or a continuous static feedback before discretization, leading to the exact computability of the controller. For this to occur, links have been pointed out to nilpotent or feedback nilpotenizable Lie algebras. In the case of finitely discretizable systems, multirate techniques have been used to steer real analytic controllable systems between arbitrary state configurations permitting motions in all the directions of controllability [21], for maneuvering space multibody structures actuated by internal forces [22] or to steer finitely nonlinear dynamics with a non-zero drift term and delayed inputs [23]. To confer robustness to the multirate digital implementation of a linearizing control strategy, when parametric uncertainties are present in the continuous-time model of a synchronous motor, nonlinear digital multirate control is combined with discrete-time adaptive schemes based on hyperstability concepts in Ref. [24], guaranteeing the stability of the whole system and the asymptotic fulfillment of the control objectives.

More recently, the problem of state feedback sampled-data stabilization of nonlinear systems under the “low measurement rate” constraint and in the presence of (not necessarily small) time delay in the measurement channel was studied in Ref. [25]. A multirate control scheme is proposed that utilizes a numerical integration scheme to approximately predict the current state from the delayed measurements. It was shown that under standard assumptions, the closed-loop multirate sampled data system is asymptotically stable in the semi global practical sense, for both the controller emulation approach and the approach based on approximate discrete-time model of the system. Finally, an illustrative example of sampled-data control of a vertical take-off and landing aircraft has been presented, that demonstrates the advantages of the proposed scheme. In Ref. [26], a Distributed Model Predictive Control (DMPC) system using multirate sampling for large-scale nonlinear uncertain systems composed of several coupled subsystems was designed. The proposed controllers were designed via Lyapunov-based MPC (LMPC) techniques, taking into account bounded measurement and communication noise and process disturbances. Sufficient conditions under which the state of the closed-loop system is ultimately bounded in an invariant region containing the origin were derived. Finally, the applicability and performance of the proposed DMPC scheme were demonstrated through a nonlinear chemical process example. In Ref. [27], a multi-rate sampled-data implementation of a

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