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Output feedback control of a mechanical system using magnetic levitation

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ABSTRACT

This paper presents an application of a nonlinear magnetic levitation system to the problem of efficient active control of mass–spring–damper mechanical systems. An output feedback control scheme is proposed for reference position trajectory tracking tasks on the flexible mechanical system. The electromagnetically actuated system is shown to be a differentially flat nonlinear system. An extended state estimation approach is also proposed to obtain estimates of velocity, acceleration and disturbance signals. The differential flatness structural property of the system is then employed for the synthesis of the controller and the signal estimation approach presented in this work. Some experimental and simulation results are included to show the efficient performance of the control approach and the effective estimation of the unknown signals.

1. Introduction

Magnetic levitation has shown its potential in many engineering fields. Practical applications of magnetic levitation can be found in vibration control systems, magnetic bearings, high-speed passenger trains as well as in other real engineering systems (see, e.g., [1–5] and references therein). Valuable nonlinear and linear control schemes based on sliding modes, feedback linearization, backstepping, classical control, neural networks, optimal control, adaptive control, and other control design approaches have been successfully applied to magnetic levitation systems. Thereby, control of magnetic levitation systems to robustly suspend a magnetic ball has been an active and challenging research topic in the few years (see, e.g., [5–16]). However, most of the contributions require measurements of position, velocity and electric current, and hence state observers should be synthesized to estimate the unavailable signals of the nonlinear dynamical system from the measurable output variable [17]. Moreover, it is well known that the nonlinear behavior of the magnetic levitation system hinders the design of state observers and output feedback tracking controllers.

Some nonlinear dynamical systems present the structural property known as differential flatness. A dynamical system is a differentially flat system if there is a set of independent outputs, called flat outputs and equal in number to control inputs, which completely parameterizes every state variable and control input [18,19]. The analysis and design of control schemes for nonlinear dynamical systems is greatly simplified by means of differential flatness. Trajectory planning and tracking constituted for a controlled nonlinear system are easily accomplished as well. Thus, nominal system trajectories can be completely described in terms of reference trajectories specified for flat output variables, without solving the system of differential equations. This allows establishing the desired behavior for the closed-loop system in the control design stage, considering possible technological constraints for the state and control variables, and energy efficiency criteria. Therefore, differential flatness qualifies as a suitable tool for proposing simple and efficient solutions to the problem of active control of vibrating mechanical systems using magnetic levitation.

Many vibrating mechanical systems can be characterized using several topological configurations of mass–spring–damper systems [20–22]. Classical dynamic vibration absorbers are modeled as mass–spring–damper secondary systems, which are coupled to the flexible mechanical system to be protected [23]. A wide variety of these vibration control devices can be found in bridges, civil structures, machine tools and other real engineering systems [21–23]. A Jeffcott rotor model can be used to properly describe

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the first vibration modes in rotating machinery [24,25]. Here, the dynamics of the responses in the x and y directions of the geometric center coordinates of the unbalanced rotating mechanical systems are described by mass–spring–damper system models. The vibration problem of metal-cutting machine tools is analyzed using mass–spring–damper models for each motion axis direction [26,27]. Mechanical suspension systems for vibration isolation of high precision industrial machinery are also practical examples of mass–spring–damper systems [28]. Thence the efficient control of mass–spring–damper mechanical systems is a high relevance research topic in practical engineering systems.

There are three fundamental control methodologies for vibrating mechanical systems described as passive, semi-active and active control [21,22]. Passive control relies on the addition of stiffness and damping to the system to reduce the primary response, and serves for stable operating conditions. Semi-active control deals with adaptive spring or damper characteristics, which are tuned according to the operating conditions. Active control achieves better dynamic performance by adding controlling actuator forces depending on feedback information of the system obtained from sensors [28,29].

The use of force control devices based on magnetic levitation represents a growing trend in active control applications of flexible mechanical systems. These electromagnetic control devices present some better performance indicators than mechanical force actuators from perspectives of useful life, energy efficiency, equipment maintenance, fast control response and high operation velocities. The absence of mechanical contact between the electromagnetic actuator and machine parts reduces some relevant problems of wearing, material fatigue, friction, lubrication, poor finishes of manufactured products, loosening of fasteners, efficiency loss, and malfunction of instrumentation. Hence magnetic levitation offers areas of opportunity for design and implementation of efficient active control schemes for flexible mechanical systems (see, e.g., [2] and references therein).

This paper presents an application of magnetic levitation to the stabilization and tracking control problem of a single degree-of-freedom mass–spring–damper vibrating mechanical system. It is shown that electromagnetically controlled flexible mechanical systems exhibit the differential flatness property. The presented control approach can be extended to fully actuated or under-actuated, differentially flat, mass–spring–damper vibrating mechanical systems with multiple degrees of freedom. For instance, one could apply the presented control approach to the active vibration control problem using active–passive vibration absorbers [30–32]. In this case, the control force is supplied by the magnetic levitation device. In the same way, the outcomes of this study can be extended to the balancing problem of rotating machinery using active magnetic bearings involving several magnetic levitation devices [2,33]. Therefore, the developments presented in this study admit a wide variety of real applications in active control of vibration. Hence, we can say that our contribution is pertinent by taking traditional magnetic levitation to a concrete application case. In this paper, an output feedback control scheme is proposed for reference position trajectory tracking tasks on a mass–spring–damper vibrating mechanical system, including its stabilization at a desired equilibrium position. It is considered that only measurements of the position output variable are available. This because the actively controlled vibrating mechanical systems are commonly equipped with position sensors (e.g., encoders and proximitors) for implementation of control polices. However, acceleration and electric current sensors could also be used. Then, the reconstruction of the unavailable signals is easily carried out. Nevertheless, the problem of control is of major interest when output measurements of a nonlinear dynamic system are only allowed due to cost reduction reasons. A Luenberger-like extended state observer is also included in the control scheme to estimate velocity, acceleration and disturbance signals. The differential flatness property exhibited by the three degree-of-freedom nonlinear system and Taylor polynomial expansions is used for the synthesis of the observer-based control scheme proposed for vibrating mechanical systems. In addition, unlike other contributions, our control and observer design approach considers electromagnetic circuit dynamics in the synthesis of a control voltage algorithm to regulate the position of the mechanical system in accordance with specified motion planning. Moreover, the electric current signal is algebraically reconstructed through the estimated signals as a bonus, thanks to the differential flatness property.

The main differentiation and originality of this contribution with respect to the previous proposals on magnetic levitation systems (e.g., [5–16]) is then summarized through the following highlights of the presented control approach. (i) The application of a magnetic levitation system is extended to the efficient active control problem of vibrating mechanical systems. (ii) An input–output mathematical model of the differentially flat vibrating mechanical system is obtained for the synthesis of the controller and extended state observer proposed in this work. (iii) An output feedback controller for stabilization and desired reference position trajectory tracking tasks is proposed for mass–spring–damper flexible mechanical systems electromagnetically controlled by voltage using position output variable measurements only, and avoiding the employ of mechanical force actuators, which is quite common in active control of vibrating mechanical systems. (iv) An asymptotic estimation approach based on differential flatness, trajectory planning and tracking, and Taylor polynomial expansion of the disturbance signal affecting the transformed input–output system dynamics is proposed to estimate velocity, acceleration and disturbance signals. (v) The dynamics of the electromagnetic subsystem is considered in the analysis and synthesis of the controller and observer.

Experimental and simulation results spotlight the efficient performance of the control approach and the effective estimation of the unknown signals. Neglected dynamics and parametric uncertainty are considered in our performance assessment as disturbance signals to be estimated by the observer. Motion planning is initially specified to smoothly transfer the system from a rest position to another. Additionally, the robustness of the control and estimation scheme against actuator saturation and additive stochastic noise corrupting the measurement and control signals is verified for a closed-loop time-varying reference position trajectory tracking task showing satisfactory results.

2. An introductory case study: control of a mass–spring–damper system

2.1. Mathematical model

To illustrate the basic ideas of the proposed active control approach based on on-line estimation of signals, consider the n degree-of-freedom (DOF) mass–spring–damper mechanical system shown in Fig. 1. The generalized coordinates are the n positions of the mass carriages, x_i, $i = 1, 2, \ldots, n$. In addition, m_i, k_i and c_i denote mass, stiffness and viscous damping associated to the i-th DOF, u represents the force control input and $y = x_1$ is the output position variable to be controlled.

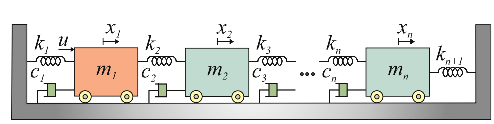

Fig. 1. Schematic diagram of a n DOF flexible mechanical system.