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Adaptive simultaneous motion and vibration control for a multi flexible-link mechanism with uncertain general harmonic disturbance

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ABSTRACT

In this paper, a new motion and vibration synthesized control system—a linear quadratic regulator/strain rate feedback controller (LQR/SRF) with adaptive disturbance attenuation is presented for a multi flexible-link mechanism subjected to uncertain harmonic disturbances with arbitrary frequencies and unknown magnitudes. In the proposed controller, nodal strain rates are introduced into the model of the multi flexible-link mechanism, based upon which a synthesized LQR controller where both rigid-body motion and elastic deformation are considered is designed. The uncertain harmonic disturbances would be canceled in the feedback loop by its approximated value which is computed online via an adaptive update law. Asymptotic stability of the closed-loop system is proved by the Lyapunov analysis. The effectiveness of the proposed controller is shown via simulation.

1. Introduction

Flexible mechanisms are increasingly utilized in many applications such as industrial robots, aircrafts and the military industry, since they have several advantages such as lower energy consumption, faster response and lower overall cost [1]. However, the flexibility property in the system would lead to the appearance of undesired vibration, which makes control of the flexible system really challenging. The main difficulties are the incompatibility between the degrees of freedom of the flexible mechanisms and the number of available inputs, as well as the interaction between the objective motion and undesired vibration [2]. It means that both motion and vibration need to be considered in the controller design and the controller must simultaneously achieve high-precision trajectory tracking and effective vibration suppression.

From a mathematical point, a flexible mechanism is often considered as a distributed parameter system, which is modeled by partial differential equations (PDEs). The PDE dynamic is difficult to control due to the infinite dimensionality of the system [3]. Usually, the FEM method [4–8] or the assumed-mode method [9,10] would be adopted to decompose the PDE into a finite number of ordinary differential equations (ODEs) [11], since many control techniques are developed on the basis of ODE systems. The vast majority of these control techniques, such as PD control

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[12], model predictive control [13], adaptive control [14], sliding control [15], and singular perturbation approach [16] et al. have been successfully conducted on single flexible link mechanisms. But control of a multi flexible-link mechanism is more complicated than control of a single flexible link mechanism. In recent years, some control methods were presented for control of the multi flexible-link mechanisms, one of which is on the basis of the application of smart materials featuring distributed actuators, such as piezoelectric patches (PZTs) [17–20]. However, the drawback of the method is that additional actuators and their accessories are needed, which is not economical from the practical point of view. To improve the operational reliability of controllers for multi flexible-link mechanisms, the control method that only uses joint actuators without extra actuators was presented. It can be classified into either the feed forward type or the feedback type [21]. The prototypical method of the feed forward type control is the input shaping technique. An input shaping technique was used in [22] to suppress vibration for the multi flexible-link mechanism, but the shaping process may alter the desired trajectory and degrade the trajectory tracking precision. Another drawback of the input shaping technique which is the open-loop control system is their inability to handle injected disturbances to the system. Hence more researchers focus on the feedback type or the synthesis of the feed forward type and the feedback type. A collocated joint PD regulator was used to control a multi-link flexible robot in [23]. A hybrid PD/PID controller was proposed to control the two-link flexible mechanism in [24]. The common defect of the above two controllers is that the derivative effect is prone to excite further vibration of flexible linkages when the desire trajectory is tracked by the PD regulator. Caracciolo and Trevisani [25] presented a control system which consists of two separated control schemes, PID and strain rate feedback, operating simultaneously for a flexible four-bar linkage. However, the vibration control force (strain rate feedback) would affect the motion control force (PID) easily, which leads to the degradation of performance on trajectory tracking. Utkin [26] presented the sliding mode (SMC) control based on the pole assignment approach for a multi-link flexible mechanism. Trajectory tracking control of a two link flexible mechanism is presented in [27] using conventional SMC. Unfortunately, sliding mode control is prone to cause chattering on the desire trajectory. A classical optimal control system is developed for vibration reduction of a flexible five-bar linkage in [28]. Ouyang et al. [29] developed pole assignment on a flexible four-bar linkage via position and velocity feedback or acceleration and velocity feedback based on the work about pole assignment of friction-induced vibration [30]. Boscariol et al. [31] proposed a constrained MPC (Model Predictive Control) system as an effective control strategy for position and vibration control of flexible link mechanisms.

The most exiting papers about the motion or vibration control design of multi-link flexible mechanisms did not consider disturbances which often appear in the general industrial environment and would degrade the system performance. Recently, some mathematical results dealing with uncertain disturbances have been presented. An active disturbance rejection control (ADRC) [32] approach using an extended state observer to estimate the disturbance and cancelling it in the feedback loop was adopted to stabilize a wave equation in [33]. Tang et al [38] used ADRC integrated with the backstepping approach to stabilize a 2×2 system of first-order linear hyperbolic partial differential equations (PDEs) subject to a boundary input disturbance. The disturbance rejection using sliding model control (SMC) integrated with the backstepping approach was proposed in [34] and [39]. Guo [35] presented adaptive stabilization for a wave equation subject to general boundary harmonic disturbances and proved the asymptotical stability of the closed-loop system. Some disturbance rejection methods have also been proved effective via the experimental investigation in [40–43].

To our knowledge, we firstly propose a hybrid linear quadratic regulator /strain rate feedback (LQR/SRF) controller with adaptive disturbance attenuation to achieve simultaneous motion and vibration control for a multi flexible-link mechanism with uncertain harmonic disturbances. In this neoteric method, nodal strain rates feedback are brought into the design of LQR controller where both rigid-body motion and elastic deformation are considered. Meanwhile, an adaptive estimator is designed to estimate the uncertain harmonic disturbance which would be attenuated in the closed-loop system. The main contribution of this paper can be summarized as:

1) A more practicable motion and vibration simultaneous control system where only joint actuators are needed for a multi flexible-link mechanism is proposed.
2) The effect of vibration suppression on good behavior of motion control can be reduced considerably due to SRF embedded in the design of LQR.
3) The active disturbance attenuation for a multi flexible-link mechanism subject to uncertain harmonic disturbances with unknown amplitudes and arbitrary frequencies at input joints is achieved via the adaptive control design.

The paper is organized as follows: Section 2 briefly outlines the general dynamic model of the planar multi flexible-link mechanisms with disturbances. The description of the LQR/SRF controller and the adaptive disturbance estimator are presented in Section 3. The proof of the asymptotical stability of the closed-loop system is shown by Lyapunov analysis in Section 4. The numerical simulation on a flexible four-bar linkage is carried out in Section 5. Finally, the conclusions and future work are provided in Section 6.