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Discrete-time dynamic output feedback input shaping control of vibration in uncertain time-delay flexible structures

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ABSTRACT

This paper proposes an observer-based discrete-time neuro-sliding mode control (NSMC) scheme combined with input shaping control for uncertain time-delay flexible structures. Only partial information of system states is known. It is shown that the proposed scheme not only guarantees closed-loop system stability, but also it effectively suppresses residual vibration and yields good robustness in the presence of state delays, input delays, parameter uncertainties, external disturbances and inaccurate impulse application instants simultaneously. The knowledge of upper bound of uncertainties is not required. Furthermore, it is shown that increasing the robustness to parameter uncertainties does not lengthen the duration of the impulse sequence. Simulation results demonstrate the efficacy of the proposed control scheme.

1. Introduction

In recent years, flexible structures have widely utilized in spacecraft, robotic systems, manufacturing equipment and so on. The operational performance and accuracy of lightly damped flexible systems are affected by residual vibrations which are generally encountered during and after movements and are usually undesirable. Therefore, the robust control of vibration in flexible structures has become an important research field. One of the most successful methods used to control flexible structures is known as input shaping [1–4]. Input shaping is implemented by a sequence of impulses, called the input shaper, together with a desired system command, and forms a new system input that yields the desired motion without vibration. However, one drawback of this method is that the exact cancellation of the residual vibration depends on the amplitudes and instants of impulse application which are related to system parameters. If amplitudes or instances at impulse application are inaccurate, then the residual vibration can lead to system performance degradation. Furthermore, conventional input shaping method does not deal with vibration caused by state delays, input delays or external disturbances either.

Several versions of input shaping control technique [5–13] have been proposed to improve the robustness to uncertainties in the damping factors and natural frequencies of flexible structures. However, the price for increasing robustness is to lengthen the duration of the impulse sequence, which results in a slower system response. Most of them focus on one mode flexible structure systems and can not be applied for multi-mode flexible structure systems. Furthermore, the residual vibration can not be suppressed while the larger natural frequency variations occur, and the vibration caused by an external disturbance has not been considered. In this paper, the proposed method can overcome those problems. Recently, a feedback controller combined with input shaping control has developed to improve the robustness to system parameter uncertainties.

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In [14], a closed-loop input shaping control method is proposed for the robustness to inaccuracies in the instants of applied impulses. In [15], a method of concurrently designing the input shaping and feedback control is developed for obtaining fast and precise point-to-point movement of a chip mounter. In [16], an adaptive input shaper is explored for providing robustness to parameter uncertainties by tuning the shaper to the flexible mode frequencies. In [17], a new adaptive control scheme is developed to increase the robustness of the shaper, even in the presence of additive noise in the system output. In [18], a comparative assessment of hybrid control schemes is presented for vibration suppression and end-point trajectory tracking of a flexible robot manipulator. In [19], an active vibration control using optimized modified acceleration feedback is developed for vibration reduction. In [20], a closed-loop input shaping control scheme is developed for uncertain flexible structure and uncertain time-delay flexible structure systems. In [21], a feedback controller with an adaptive input shaper is developed for single-link flexible manipulators. In [22], an inverse shaper in the feedback configuration is developed for the vibration reduction. However, these methods assumed that all states of systems are available and are developed in continuous-time systems. In many practical systems, full measurement of the states is not feasible and only partial information of the states is known. Furthermore, using computers or chips in practice to implement the controller becomes more and more important nowadays, and discrete-time controller has gained more and more attractive attention recently. To the best of the author's knowledge, very little attention has been paid to the problem of input shaping control for a class of uncertain time-delay flexible structure systems in discrete-time domain by using output feedback only, which is still open in the literature. This has motivated our research.

The main contribution of this paper is to develop an observer-based discrete-time NSMC scheme combined with input shaping method to suppress residual vibration of uncertain time-delay flexible structures with immeasurable states. The algorithm is base on input shaping and discrete-time sliding mode control (SMC) [23–33]. It will be shown that the proposed scheme guarantees the stability of closed-loop system and suppresses residual vibration in the presence of state delays, input delays, parameter uncertainties, external disturbances and inaccurate impulse application instants simultaneously. The proposed method has the following attractive features: (1) the control design is rather straightforward. The stability of overall closed-loop systems is guaranteed and the suppression of residual vibration is achieved. (2) the order of the motion equation in the quasi-sliding mode is equal to the order of the original system, rather than reduced by the number of dimension of the control input. The robustness of the system can be guaranteed throughout the entire response of the system starting from the initial time instance. (3) the proposed scheme is developed with partial information of the system states only. The proposed scheme needs not be of switching type. Neither chattering phenomenon will occur nor the knowledge of upper bound of uncertainties is required. Therefore, the proposed technique is easy to implement in the application. (4) the proposed scheme not only provides good performance and robustness in the presence of state delays, input delays, parameter uncertainties, external disturbances and inaccurate impulse application instants simultaneously, but also shows that increasing the robustness in parameter uncertainties does not lengthen the duration of the impulse sequence. Therefore, the propose scheme is more flexible and better than the conventional input shaping control method.

The organization of this paper is as follows. Section 2 briefly reviews the description of input shaping control. An observer-based discrete-time NSMC scheme combined with input shaping control is developed in Section 3. The selection of sliding surface and the satisfaction of reaching conditions have been addressed. Section 4 provides results from numerical simulations and comparison of these results to those from methods in the existing literature. Finally, a conclusion is provided in Section 5.

2. Input shaping control

Input shaping control is implemented to reduce the residual vibration of flexible structure systems by convolving the command input with a sequence of M impulses, also known as the input shaper. Suppose a sequence of M impulses is applied to the flexible system with one vibratory mode. These impulses have amplitudes $I_{1,i},\quad i = 1,\ldots,M$, and are applied at times $t_{1,i},\quad i = 1,\ldots,M$. If amplitudes and instances at impulse application are accurate, then system performance will result in zero vibration. From [1,3], the corresponding amplitudes and instances of M impulses can be expressed as

$$I_{1,i} = \frac{\binom{M-1}{i-1}K_1^{i-1}}{\sum_{j=0}^{M-1}\binom{M-1}{j}K_1^{j}},\quad t_{1,i} = (i-1)\frac{\pi}{\omega_1\sqrt{1-\zeta_1^2}},\quad K_1 = e^{\frac{-\zeta_1\pi}{\sqrt{1-\zeta_1^2}}},\quad i = 1,\ldots,M, \tag{1}$$

where $I_{1,i}$ is the amplitude of the ith impulse and $t_{1,i}$ is the time of the ith impulse. Then, the shaped impulse sequence can be expressed

$$\Psi_1 = I_{1,1}\delta(t) + I_{1,2}\delta(t - t_{1,2}) + \cdots I_{1,M}\delta(t - t_{1,M}), \tag{2}$$

where $t_{1,1} = 0$ and $\delta(\cdot)$ is an impulse function. It is noted that the amplitudes and the instants in (1) depend on the system parameters, i.e. the system natural frequency ω_1 and the damping ratio ζ_1. To increase the robustness to uncertainties in the natural frequency and the damping ratio, one approach is to lengthen the duration of the impulse sequence which results in a slower system response. Hence, it is desired to increase the robustness of the system without adding any impulses to the shaper.