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Vibration control of uncertain multiple launch rocket system using radial basis function neural network

Bo Li, Xiaoting Rui *

Institute of Launch Dynamics, Nanjing University of Science and Technology, Nanjing 210094, PR China

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ABSTRACT

Poor dispersion characteristics of rockets due to the vibration of Multiple Launch Rocket System (MLRS) have always restricted the MLRS development for several decades. Vibration control is a key technique to improve the dispersion characteristics of rockets. For a mechanical system such as MLRS, the major difficulty in designing an appropriate control strategy that can achieve the desired vibration control performance is to guarantee the robustness and stability of the control system under the occurrence of uncertainties and nonlinearities. To approach this problem, a computed torque controller integrated with a radial basis function neural network is proposed to achieve the high-precision vibration control for MLRS. In this paper, the vibration response of a computed torque controlled MLRS is described. The azimuth and elevation mechanisms of the MLRS are driven by permanent magnet synchronous motors and supposed to be rigid. First, the dynamic model of motor-mechanism coupling system is established using Lagrange method and field-oriented control theory. Then, in order to deal with the nonlinearities, a computed torque controller is designed to control the vibration of the MLRS when it is firing a salvo of rockets. Furthermore, to compensate for the lumped uncertainty due to parametric variations and un-modeled dynamics in the design of the computed torque controller, a radial basis function neural network estimator is developed to adapt the uncertainty based on Lyapunov stability theory. Finally, the simulated results demonstrate the effectiveness of the proposed control system and show that the proposed controller is robust with regard to the uncertainty.

1. Introduction

Multiple Launch Rocket System (MLRS) is a motor-mechanism coupling system, which is used to carry and orient the rockets to the target. It is equipped with two servomotors and set of gears to provide the elevation and azimuth angles for aiming the rockets. A jet force generated by firing a salvo of rockets may lead on the launcher to produce angular vibrations. Theoretical and experimental results exhibit that a very small amplitude vibration of the launcher may cause remarkable rocket dispersion [1]. Therefore, such vibration has restricted the development of MLRS. Recently, vibration control has been widely used in the area of MLRS and become an important research field and development direction [2–11]. It is generally believed that difficulties are unavoidable in the design of controller when uncertainties and nonlinearities exist in mechanical systems. And MLRS faces parametric variations of mass, moment of inertia and stiffness during launching.

* Corresponding author.
E-mail address: ruixt@163.net (X. Rui).

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Consequently, the dynamic model of MLRS is inherently nonlinear with time-varying and coupling characteristics. Besides, for a complex mechanical system such as MLRS, it is impossible or difficult to formulate an accurate dynamic model. The systematic nonlinearities and the uncertainties, i.e., parametric variations and un-modeled dynamics have brought huge challenges in designing a robust vibration controller for MLRS.

The earliest vibration control started with passive methods. In the early 1980s, Cochran et al. [2–4] attempted the passive control and discussed the potential of a rocket launcher as passive control. They installed an elastic component at the tip of the launcher and utilized rocket imperfections, e.g., thrust misalignment and mass eccentricity, to bring about the vibration of launcher/rocket system which can in turn lead to rocket initial disturbance. Then, the ballistic deflection due to rocket imperfections can counteract that due to the initial disturbance by optimizing system parameters. However, this passive controller worked only in the case where the inertia of the launcher is less than that of the rocket. Later on, Chen [5] carried on a study on the mechanisms of launcher/rocket passive controller. Based on the works of Cochran and Chen, Zhao et al. [6] presented a novel rocket passive control method where they directly installed an elastic component on rocket instead of launcher, and thus there is no need to control launcher and rocket together. Hence, their passive control performance is superior to Cochran's because the inertia of the former system is smaller. However, the above-mentioned passive control methods can only cut down the vibration due to rocket imperfections except that due to the jet force. Moreover, the passive method can only control the vibration responses up to a certain limit owing to the lack of energy needed to handle larger responses. The major focus lies that the traditional passive method cannot guarantee the effectiveness when the high control accuracy and fast response are required in practical applications.

To remove such constraint from passive control, active methods that can provide energy to attenuate vibration quickly and effectively have been introduced [7–11]. Nevertheless, the involved controllers in these studies are mainly linear and their performances are usually influenced by the systematic nonlinearities in actual applications. Subsequently, some advanced control methods are introduced into control of MLRS. Chen et al. [12] presented a back-stepping sliding mode controller, which combines the back-stepping control with the classical sliding mode control. In Zhang et al. [13], an optimal internal mode and sliding mode control is designed in order to control the position of a rocket launcher using a Permanent Magnet Synchronous Motor (PMSM) as actuator. The computed torque control, which is a special method of feedback linearization of nonlinear systems, is widely used to robotic manipulators by cancelling nonlinear terms [14–16]. Inspired by this control method, Dokumaci et al. [17] first introduced it into the control of a rocket launcher system. It is worth noticing that the computed torque controller is effective based on the assumption that no uncertainties exist in actual applications. Ref. [17] neglected the uncertainties of MLRS. Furthermore, all of the above researches are concentrating only on either the servomotors or the mechanisms. However, the motor-mechanism coupling dynamic model of MLRS has seldom been discussed.

Many intelligent algorithms are used to deal with the uncertainties. Neural network is one of the most effective techniques for its universal approximation property and has been applied in [18–25]. In this paper, the computed torque controller integrated with Radial Basis Function Neural Network (RBFNN) is proposed to control the vibration of MLRS considering the nonlinearities and uncertainties in practical applications. Specifically, pioneering works that proposed the computed torque controllers combined with neural network have been reported. In order to control the position of a slider of a motor-quick-return servo mechanism, a hybrid computed torque controller is designed and the uncertainty is adapted by a Fuzzy Neural Network (FNN) in [26]. Miao et al. [27] derived a torque controller by computed torque law, in which a recurrent neural network algorithm was developed to deal with the uncertainties of system and the closed-loop stability analysis was carried out based on a technical lemma. Aimed at handling the structured and unstructured uncertainties in a space robot system, Kumar and Panwar [28] proposed an intelligent controller including the computed torque controller and RBFNN estimator. Considering the fact that it is impossible to design a high performance computed torque controller owing to the uncertainties of a servomotor drive system, Lin et al. proposed a recurrent fuzzy neural cerebellar model articulation network to estimate the uncertainties in [29]. These researches mainly focus on removing the influence of uncertainties on the control system by estimating and compensating for them. Another effective scheme is to adapt the controller parameters by neural network algorithm. The related works can be found in [30–33].

In this paper, the vibration control of MLRS actuated by a PMSM drive with a computed torque controller using an RBFNN uncertainty estimator is studied to provide an alternative for reducing rocket dispersions. The nonlinear model of the motor-mechanism coupling MLRS is established. When the computed torque controller is designed, the uncertainties including parametric variation and un-modeled dynamics could result in a poor control performance. To overcome this difficulty, a RBFNN estimator is implemented to compensate for them. The weight and threshold values of the RBFNN are adaptively updated based on Lyapunov stability theory and the asymptotic stability of the closed-loop system is guaranteed. The novelties of the proposed control algorithm are:

(1) Contrary to the previous works [8,12,13] that only considered the dynamic model of either the motor or the mechanism in designing the controller, the present work has taken the dynamic model of the motor-mechanism coupling MLRS into account.
(2) The resulting RBFNN controller has a simple structure that avoids a high computational burden, and can effectively improve the control performance against the uncertainties of the system and guarantee the stability of the closed-loop system.