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Synchronization analysis and control of three eccentric rotors in a vibrating system using adaptive sliding mode control algorithm

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ABSTRACT

In this paper, self- and controlled synchronizations of three eccentric rotors (ERs) in line driven by induction motors rotating in the same direction in a vibrating system are investigated. The vibrating system is a typical underactuated mechanical-electromagnetic coupling system. The analysis and control of the vibrating system convert to the synchronization motion problem of three ERs. Firstly, the self-synchronization motion of three ERs is analyzed according to self-synchronization theory. The criterions of synchronization and stability of self-synchronous state are obtained by using a modified average perturbation method. The significant synchronization motion of three ERs with zero phase differences cannot be implemented according to self-synchronization theory through analysis and simulations. To implement the synchronization motion of three ERs with zero phase differences, an adaptive sliding mode control (ASMC) algorithm based on a modified master–slave control strategy is employed to design the controllers. The stability of the controllers is verified by using Lyapunov theorem. The performances of the controlled synchronization system are presented by simulations to demonstrate the effectiveness of controllers. Finally, the effects of reference speed and non-zero phase differences on the controlled system are discussed to show the strong robustness of the proposed controllers. Additionally, the dynamic responses of the vibrating system in different synchronous states are analyzed.

1. Introduction

Vibrating machines are utilizing vibrating principles to perform kinds of typical industrial tasks, such as conveying, screening, separating, dehydrating, grinding, discrete material shaping, transmitting information and so on [1,2]. In many vibrating machines, two or more components are required to operate synchronously. Blekhman [3] firstly proposed the synchronization theory of mechanical exciters. With the development of synchronization theory and technology, self-synchronization theory is introduced into many vibrating machines excited by two ERs to replace gears or chains in forced synchronization [4]. In the small size self-synchronous vibrating machines, two ERs are separately driven by induction motors installed on a rigid frame directly, where the structures of vibrating machines are simple. However, when the sizes of vibrating machines are large requiring more exciting forces, the induction motors cannot be installed on the rigid frame

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directly to provide sufficient powers because of their power limitations. In these cases, the structures will change more complex and their applications will cover larger areas [5]. Using more induction motors driving more ERs is a reasonable idea to overcome the shortages. Nevertheless, with the increase of the number of ERs, the conditions of implementing self-synchronization motion of multiple ERs will become more difficult to be satisfied or cannot be satisfied in some cases [6]. In these cases, the controlled synchronization of multiple ERs is a good choice.

As a key issue in industrial production, a number of researchers have investigated the controlled synchronization of multiple components in the mechanical fields. Tomizuka et al. [7] studied the motion synchronization problem of two direct current (DC) motors by utilizing an adaptive feedforward control law. Deng et al. [8] studied the motion synchronization of two permanent magnet synchronous motors. In their work, a synchronization controller based on load observer was designed via cross-coupling structure and interval matrix and speed, position and current signals were taken as controlled signals. Li et al. [9] studied the speed tracking and synchronization of multiple induction motors by using an adaptive sliding mode control algorithm based on the ring coupling control structure. Zhang et al. [10] investigated the chaotic speed synchronization control of multiple induction motors. To achieve the chaotic speed control of each motor, the direct torque control using the stator flux regulation method was employed. Moreover, to achieve the speed synchronization of multiple motors, an adaptive time-delayed feedback control algorithm based on the master-slave control structure was employed. Instead of the motion synchronization of multiple motors, Cheng et al. [11,12] studied the tracking and synchronization control for multi-axis motion system. They expanded the motion synchronization to synthesis control problem of tracking and synchronization. Moreover, they implemented an adaptive robust control scheme to achieve good tracking and synchronization effectiveness. Sun and Mills [13] introduced the motion synchronization to the control of two manipulator systems. They incorporated the cross-coupling technology into adaptive control architecture by feedback. More, Sun [14] expanded the motion synchronization of two manipulators to position synchronization of multiple motion axes by using the same method. Sun and Chiu [15] addressed the motion synchronization problem for a dual-cylinder electro hydraulic lift system by using a nonlinear control algorithm. Chen et al. [16] also studied the motion synchronization of the dual-cylinder system. But the control law was different with that of Sun and Chiu. They proposed an integrated fuzzy controller to obtain the motion synchronization for the system. Different with their works, Mao et al. [17] proposed a hybrid control method including feedforward control and fuzzy feedback control to guarantee the synchronization motion of dual-cylinder system. In some special applications, the tension and synchronization control should be implemented simultaneously. Yanbo et al. [18] studied the tension and synchronization control problem of a wide-fabric and heating-shaping machine. They applied a variable gain intelligence control scheme based on the conventional PID algorithm. Based on Grey model theory, Chuang et al. [19] proposed a novel modified MIMO discrete pseudo model following an integral variable structure control for the tension and synchronization control of a dual motor system. The motion synchronization problem was also widely addressed in the servo systems. Sencer et al. [20] studied the motion synchronization in dual spindle servo systems by using a continuous time sliding mode control (SMC) algorithm. Ishizaki et al. [21] studied the motion synchronization in a linear motor driven gantry type of machine tool. They proposed a novel PD type detachable cross-coupling controller for P-PI controlled dual servo feed drive systems. Chu et al. [22] introduced an optimization method to the control of synchronization error of dual feed drives in a servo system. They developed the first order approximate model of the system and designed a cross-coupled optimal synchronization controller to minimize the synchronization error. Lin et al. [23] proposed a digital signal processor (DSP)-based cross-coupled intelligent complementary SMC system for a dual linear motor servo system and verified the effectiveness by experiments. However, from above researches, the controlled synchronization problem of multiple induction motors in a vibrating system is investigated scarcely. Miklos and Szabo [24] studied the control of dual DC motors in a vibrating system. But they adopted the control technology on two DC motors to make frequency and amplitude independent of a vibrating system. Moreover, the controlled synchronization of multiple DC motors more than two was not also investigated in their works. Fradkov et al. [25] studied the approximate multiple frequency and phase controller synchronization for three-rotor vibration unit with vary payload via two PI algorithms. However, the important induction motor's model was not considered.

In the present research, the synchronization analysis and control of three ERs in line driven by induction motors rotating in the same direction in a vibrating system are studied. The outline of this article is the following. In Section 2, a mechanical-electromagnetic coupling model of the vibrating system is developed, which is a typical underactuated system. To obtain desired working state of the vibrating system, the investigation of the complex system converts to the motion synchronization of three ERs. In Section 3, according to the self-synchronization theory, the synchronization and stability of the vibrating system are analyzed and the limitation of the self-synchronization is explained. In Section 4, an ASMC algorithm based on a modified master–slave control strategy is used to implement speed tracking and phase and speed synchronization of three ERs. Furthermore, Lyapunov theorem is adopted to prove the stability of the controlled system. In Section 5, the simulations are operated to verify the effectiveness and robustness of the proposed control approach. Compared with the self-synchronization of three ERs, the advantages of controlled synchronization are presented. Additionally, the dynamic responses of the vibrating system in different synchronous states are discussed. Finally, some brief conclusions are listed.

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