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Composite synchronization of three eccentric rotors driven by induction motors in a vibrating system

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ABSTRACT

This paper addresses the problem of composite synchronization of three eccentric rotors (ERs) driven by induction motors in a vibrating system. The composite synchronous motion of three ERs is composed of the controlled synchronous motion of two ERs and the self-synchronous motion of the third ER. Combining an adaptive sliding mode control (ASMC) algorithm with a modified master-slave control structure, the controllers are designed to implement controlled synchronous motion of two ERs with zero phase difference. Based on Lyapunov stability theorem and Barbalat's lemma, the stability of the designed controllers is verified. On basis of controlled synchronization of two ERs, self-synchronization of the third ER is introduced to implement composite synchronous motion of three ERs. The feasibility of the proposed composite synchronization method is analyzed by numerical method. The effects of motor and structure parameters on composite synchronous motion are discussed. Experiments on a vibrating test bench driven by three ERs are operated to validate the effectiveness of the proposed composite synchronization method, including a comparison with self-synchronization method.

1. Introduction

Recently, with the rapid development of industrial production, the modern manufacturing equipment with high speed, high accuracy, high capacity and high efficiency is needed. To satisfy these requirements, the traditional mechanical approach is inapplicable and multi-axis motion control technology is proposed and widely utilized in many types of equipment, such as robots, multi-axis computer numerical control (CNC) machine tools, printing machines, propeller aircraft, unmanned aerial vehicle, and high-speed trains [1–4]. However, multi-axis control technology is used scarcely in vibrating machines. Self-synchronization theory of two ERs was firstly proposed by Blekhman [5]. Then, introducing the self-synchronization theory into vibrating machines, many various self-synchronous vibrating machines are designed and used widely in engineering to replace the forced synchronization, such as self-synchronous vibratory feeder, self-synchronous vibratory conveyor, self-synchronous vibrating screen, etc. Moreover, in most self-synchronous vibrating machines, two ERs driven by induction motors are directly installed on the body so that their structures are very simple [6]. However, when the number of ERs is more than two, the vibrating machines are difficult to operate in desired working mode and their working efficiency will even decrease in some cases [7,8]. To solve this disadvantage, using multi-axis control technology to implement controlled synchronization of multiple ERs is a good choice [9]. But the application of controlled synchronization

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method will increase the cost. Therefore, combining self-synchronization theory and controlled synchronization method, a composite synchronization method of three ERs is proposed to obtain the desired working mode of vibrating machine in our work.

A number of researches have been performed to analyze self-synchronization of multi-ERs in various vibrating systems. Wen et al. [6] investigated the self-synchronization problem of two ERs in the vibrating machines by using average perturbations and Hamilton principle. In their works, the synchronization and stability criterions of synchronous state were deduced and used to design plane and spatial motion self-synchronous vibrating machines with dual-motors. Zhao et al. [10–13] proposed an average method of modified small parameters by introducing small parameters into average perturbation method. In their works, the synchronization of two ERs was converted to a problem on the existence and stability of zero solutions of perturbed equations. On basis of their works, Zhang et al. [7,8,14–16] expanded the self-synchronization problem of two ERs to that of three and even N ERs by using the average method of modified small parameters and verified by experiments. From their works, the general theoretical analysis method of self-synchronization of multi-ERs in the vibrating system is developed. Dimentberg et al. [17] investigated the transient self-synchronization of two rotating shafts by using numerical simulation. In their works, even if two rotating shafts operated self-synchronously in steady state, the transient self-synchronization could not be implemented possibly. Danuta and Maciej [18] studied self-synchronization of two ERs driven by two DC motors in a nonlinear vibrating system. In their works, there appeared the periodic motions such as super- and sub- harmonic resonance motions and the chaotic motion in some special conditions. Palacios et al. [19] investigated the self-synchronization of two unbalanced DC motors mounted on an elastic support with nonlinear stiffness and damping. Balthazar et al. [20] also researched the self-synchronization of two unbalanced DC motors. However, two DC motors were supported by a flexible portal frame structure. Djanan et al. [21,22] analyzed self-synchronization of two and three ERs driven by DC motors on rectangular plates. Recently, Zhang et al. [23] studied the vibratory synchronization transmission of a cylindrical roller with dry friction in a vibrating system based on self-synchronization of two exciters.

In the same time, there are also many researches to address controlled synchronization problems of multi-motors or axes in different types of mechanical systems. Incorporating an ASMC technique into a ring coupling synchronization control structure, Li et al. [24] studied speed tracking and synchronization of multiple motors. According to the engineering practices, Deng et al. [25] researched speed, position and current signals synchronizations of two coupling permanent magnet synchronous motors (PMSMs) with nonlinear constraints. Li et al. [4] compared different synchronization control techniques for traction motors of high-speed trains. In vertical ship lift, Gang Yang and Jiabing Zhang [26] proposed a relative coupling compensation of multi-motor synchronous control strategy to improve synchronicity of the main hoist system. To implement accurate motion control for multi-axes motion systems, Cheng et al. [27] used an adaptive robust control scheme to synthesize the compensator for tracking and synchronization considering cross-coupling dynamics among axes. Sencer et al. [28] addressed the problem of synchronization of dual spindle in servo systems by using a continuous time SMC algorithm. Parkkinen et al. [29] studied motion synchronization of two elastic tooth belt drive system by cross-coupled control strategy.

However, from above references, there are few researches on composite synchronization of multiple motors or axes in the vibrating systems. In our work, composite synchronization of three ERs driven by three induction motors separately in a vibrating system is studied. In Section 2, combining the induction motor's model with the dynamic model of a vibrating system, the electromechanical coupling model of the vibrating system is developed. In Section 3, the composite synchronization method is proposed by combining controlled synchronization method with self-synchronization method. In Section 4, the numerical analysis and simulations are operated to explain the feasibility of the proposed composite synchronization method. Moreover, the effects of motor and structure parameters are discussed. In Section 5, experiments on a vibrating test bench are operated to show the effectiveness of the proposed composite synchronization method and compared with the self-synchronization method. Section 6 presents some conclusions.

2. Mathematic model of a vibrating system

In engineering, the structures of many vibratory machines, such as feeding troughs of vibratory feeders, screen boxes of vibratory screens, conveying troughs of vibratory conveyors, etc, are usually welded through steel plates and supported by some springs. Usually, the working frequencies are much higher than the natural frequencies of rigid motions of structures and lower than those of elastic vibrations of steel plates. Therefore, to analyze the synchronization of multi-eccentric rotors (ERs) driven by induction motors separately in such vibrating systems, the elastic vibrations of steel plates can be neglected and the structures can be simplified as rigid bodies. Fig. 1 shows the mathematic model of a vibrating system driven by three ERs. As demonstrated, the body is supported by two springs providing the stiffness and damping of the vibrating system in the x-, y- and ψ- directions. Three induction motors in line driving three ERs separately are installed symmetrically on the body as exciters. The motor 1 rotates in clockwise direction, which is installed on the right side. The motors 2 and 3 rotate in anticlockwise direction, which are installed on the middle and left side, respectively. o represents the center of body, and o_1, o_2 and o_3 represent the rotating centers of three ERs, respectively. The rotating radiuses of three ERs are same and represented by r. The distances between the center of body and the rotating centers are different and represented by l_1, l_2 and l_3, respectively, where $l_1 = l_3 > l_2 \gg r$. The installation angles of three motors are represented by θ_1, θ_2 and θ_3, where