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Research article

Stabilization and synchronization for a mechanical system via adaptive sliding mode control

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ABSTRACT

In this paper, we investigate the synchronization problem of chaotic centrifugal flywheel governor with parameters uncertainty and lumped disturbances. A slave centrifugal flywheel governor system is considered as an underactuated following-system which a control input is designed to follow a master centrifugal flywheel governor system. To tackle lumped disturbances and uncertainty parameters, a novel synchronization control law is developed by employing sliding mode control strategy and Nussbaum gain technique. Adaptation updating algorithms are derived in the sense of Lyapunov stability analysis such that the lumped disturbances can be suppressed and the adverse effect caused by uncertainty parameters can be compensated. In addition, the synchronization tracking-errors are proven to converge to a small neighborhood of the origin. Finally, simulation results demonstrate the effectiveness of the proposed control scheme.

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1. Introduction

In recent years, chaos and its synchronization have found application in power converters, chemical reactions, secure communications, biological systems, information processing and, in particular, mechanical systems. It has been demonstrated that two or more chaotic systems can synchronize by linking them with mutual coupling or with a common signal. Many methods have been presented for the control and synchronization of chaotic systems such as adaptive control [1–4], robust control [5–8], sliding mode control [9–12], etc.

The centrifugal flywheel governor is a particularly interesting nonlinear dynamical system, and it plays an important role which automatically controls the speed of an engine and prevents the damage caused by a sudden change in load torque. Moreover, the parallel work of multiple centrifugal flywheel governor systems can improve the work efficiency and safety [13]. However, the centrifugal flywheel governor system often display a variety of dynamic behavior such as periodic and chaotic motion when the existence of external disturbances and system parameter uncertainty, and this dynamic behavior not only degrades the performance of control system, but also sometimes may cause system instability. Recent research has identified various forms of centrifugal flywheel governor with parameter uncertainty and external disturbance. In [14], a parametric open-plus-closed-loop method is proposed to suppress chaos, which is capable of switching from chaotic motion to any desired periodic orbit. The chaotic behavior of a centrifugal flywheel governor system with spring has been studied in [15]. Sotomayor et al. [16] have studied the Lyapunov stability and the hopf bifurcation in a system coupling a hexagonal centrifugal governor with a steam engine, and it can give sufficient conditions for the stability of the equilibrium state. Zhang et al. [17] have studied the chaotic behaviors in the fractional order autonomous and nonautonomous nonlinear systems of rotational mechanical system with a centrifugal governor and have proposed an approximation approach of fractional operator to stabilize the chaotic motion. In [18], a robust adaptive control method based on finite-time technique is proposed to synchronize the non-autonomous centrifugal flywheel governor system with input nonlinearity.

Although the above mentioned control algorithms have obtained good results in previous studies, there has no rigorous treatment of chaos and synchronization control of under- actuated centrifugal flywheel governor system with the uncertain system parameters and external disturbance. For underactuated centrifugal flywheel governor, i.e., system with fewer actuators than degrees-of-freedom, chaos

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and synchronization control is an active research topic. The study of this system is motivated by the fact that it is usually costly and often not feasible to fully actuate autonomous centrifugal flywheel governor due to reliability, complexity, and efficiency considerations. In all previous works in this subject [14–18] (Only some representative studies are recited here for the limited space), synchronization of chaotic centrifugal flywheel governor are done by designing and applying three control signals, although, in real application, using three control input to a chaotic centrifugal flywheel governor is inappropriate, and in several application, impossible.

In this paper, an adaptation synchronization control law combining both the merits of the Nussbaum gain method and sliding mode control technique is used to achieve chaos synchronization of two centrifugal flywheel governor systems in spite of the existence of lumped disturbances and parameters uncertainty. First of all, a synchronization error system is constructed by using the master and slave centrifugal flywheel governor, the slave centrifugal flywheel governor is considered as an underactuated following-system which a control input is designed to follow the master centrifugal flywheel governor. Then, two sliding mode surfaces are designed into the closed-loop system in order to introduce the information of each error-subsystem. To tackle lumped disturbances and uncertainty parameters, a novel synchronization control law is developed by employing adaptation compensation method and Nussbaum gain technique. By using the proposed method, unknown lumped disturbances can be suppressed and the adverse effect caused by uncertainty parameters can be compensated. Moreover, the designed control law without the requirement that a priori knowledge of chaotic centrifugal flywheel governor. It is proved that, with the proposed controller, the synchronization errors are stable and ultimately converge to the neighborhood of the stable point. Finally, simulation results demonstrate the effectiveness of the proposed control law.

The remainder of this paper is organized as follows: in Section 2, the mathematical model used to investigate the synchronization problem of chaotic centrifugal flywheel governor system is presented. The control solution is presented in Section 3. Numerical simulations in Section 4 are used to illustrate the effectiveness of the control method. Finally, a brief conclusion is drawn in Section 5.

2. System description and preliminaries

2.1. The model of centrifugal flywheel governor

The centrifugal flywheel governor is a particularly nonlinear mechanical system, which provides an important role in controlling the speed of an engine and preventing it from being damaged by sudden changes in the load torque. Centrifugal flywheel governor system is depicted in Fig. 1. The rotation operation of flywheel is driven by the motor. The flywheel is connected to the axis through transmission gear, that means the axis rotation with angular velocity ω can be extended by one or several times. A linear spring of stiffness ϑ and two balls combining rods are jointed to a sleeve over the axis. Vapor's flux Q in the engine is adjusted by a mechanical governor on the sleeve, which is set to make the flywheel rotate at a certain angular velocity ω_0. Moreover if $\Delta\omega = \omega - \omega_0 \neq 0$, the balls can move outward or inward, and the sleeve can also slide up or down. The mathematical model of the centrifugal flywheel governor is given by [14,15]:

$$\begin{cases} \ddot{\psi} = \left(\vartheta/M + n^2\omega^2\right)\sin\psi\cos\psi - \bar{\eta}\sin\psi - b\dot{\psi} + f_1(\psi, \dot{\psi}, \omega, t) \\ \dot{\omega} = \left(\zeta\cos\psi - F\right)/I - a\sin\upsilon t + f_2(\psi, \dot{\psi}, \omega, t) \end{cases} \tag{1}$$

where ψ is the angle between the rotation axis and the rods; ω and I are the angular velocity of the flywheel rotation and the inertia moment of the machine, respectively; l is the rods length; ϑ and M are linear spring factor of stiffness and the mass of the ball, respectively; $f_1(\psi, \dot{\psi}, \omega, t)$ and $f_2(\psi, \dot{\psi}, \omega, t)$ are the lumped disturbance including theexternal disturbance, noise and model error; F, ξ, a, b, and n are uncertain system parameters; and $\upsilon \triangleq g/l$, $\bar{\eta} \triangleq \vartheta/M + \upsilon$ with $g = 9.8$.

It is worth noting that the dynamic behavior of centrifugal flywheel governor system exhibits the chaotic motion which appears frequently in the application and has proved to be a source of performance degradation. Let $x_1 = \psi, x_2 = \dot{\psi}$ and $x_3 = \omega$, Eq. (1) can be rewritten as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \left(\vartheta/M + n^2x_3^2\right)\sin x_1\cos x_1 - \bar{\eta}\sin x_1 - bx_2 + f_1(x_1, x_2, x_3, t) \\ \dot{x}_3 = \left(\zeta\cos x_1 - F\right)/I - a\sin\upsilon t + f_2(x_1, x_2, x_3, t) \end{cases} \tag{2}$$

In the following, the chaos synchronization problem is described.

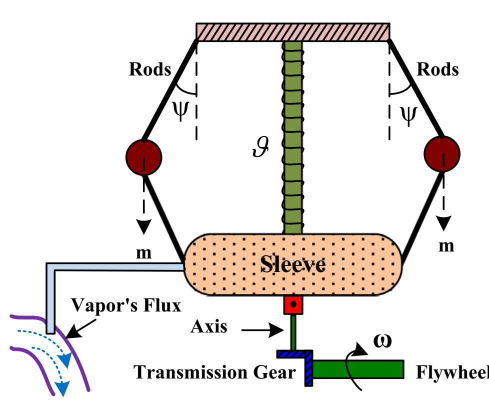

Fig. 1. Centrifugal flywheel governor system model.

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