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A compound control method for the rejection of spatially periodic and uncertain disturbances of rotary machines and its implementation under uniform time sampling

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ABSTRACT

In this paper, a compound control which combines a spatial internal model with a linear extended state observer (LESO) is proposed for continuously rotating machines. It is implemented digitally based on a uniform time sampling. An angular position-based internal model is synthesized in the spatial domain to suppress the spatially periodic disturbances existing in rotary machines, which is actuated with a fixed sampling period by introducing the angular position to the internal model in real-time. Further, an LESO is designed to estimate non-periodic disturbances and uncertain dynamics acting on the system so as to reduce the steady state error of the position output with respect to ramp angular position reference input. Comparisons and experimental results are presented to illustrate the feasibility and effectiveness of the compound control method.

1. Introduction

Rotary machines are widely used in real-world industrial applications, such as disk actuators, robot manipulators, testing tables, laser printers and industrial manufacturing. In these motion control systems, high tracking accuracy as well as high operation smoothness is a key performance index. Such systems face various disturbances and uncertainties. For a continuously rotating machine of which the load is driven by an electric motor with a fixed or variable angular velocity, most of the disturbances are periodic in terms of the angular position, but their periods vary in the time domain (Cnang, Shim, & Park, 2006; Ramos, Cortés-Romero, & Coral-Enriquez, 2015; Tammi, 2008; Tomizuka, 2008). For example, the motor ripple torque of permanent magnet synchronous motor (PMSM) is one of the primary disturbance sources, which mainly consists of electromagnetic ripple torque and cogging ripple torque. Particularly, the electromagnetic ripple torque, produced by the interaction between the rotor permanent magnet and the stator current, is hard to restrain owing to materials, components and processing technique. Physical analysis and experimental study indicate that the fundamental and harmonic components of the motor ripple torque are inherently spatially periodic, i.e., the frequency spectrum is stationary with respect to an angular position coordinate (Gieras, 2004).

In the control problems involving periodic signals, the internal model principle plays a fundamental role (Francis & Wonham, 1976; Hara, Yamamoto, Omata, & Nakano, 1998; Liu & Gao, 2010; Rugh & Shamma, 2000). However, typical internal model is time-based since it is synthesized and operated in the time domain. Thus, one of the key steps is to determine the time period or frequency of the reference input or disturbance. To ensure the effectiveness of the design, an underlying assumption is that the reference command or disturbance signal is stationary in the sense of time, i.e., the frequency spectrum of the signal does not vary with time. However, this assumption is seriously violated for control problems where periods and frequencies of the specific signals are mostly time-varying. For example, in the cam-follower system shown in Fig. 1(a) (Tsai & Lee, 1999) the output displacement of the follower x_f always has a period of 2π rad in terms of the angular position although the period is time-varying in the time domain, as illustrated in Fig. 1(b). For such systems, the time-domain internal model is not applicable.

To overcome this drawback, some new approaches have been proposed in the framework of repetitive control scheme in the last few years. In Olm, Ramos, and Costa-Castello (2010, 2011) and Ramos, Costa-Castello, and Olm (2012), a method is investigated by means of an adaptive change of the sampling period of the digital controller. High-order repetitive control is introduced either to improve the robustness for time-dependent uncertainty or to reduce the sensitivity for non-periodic inputs (Chang, Suh, &

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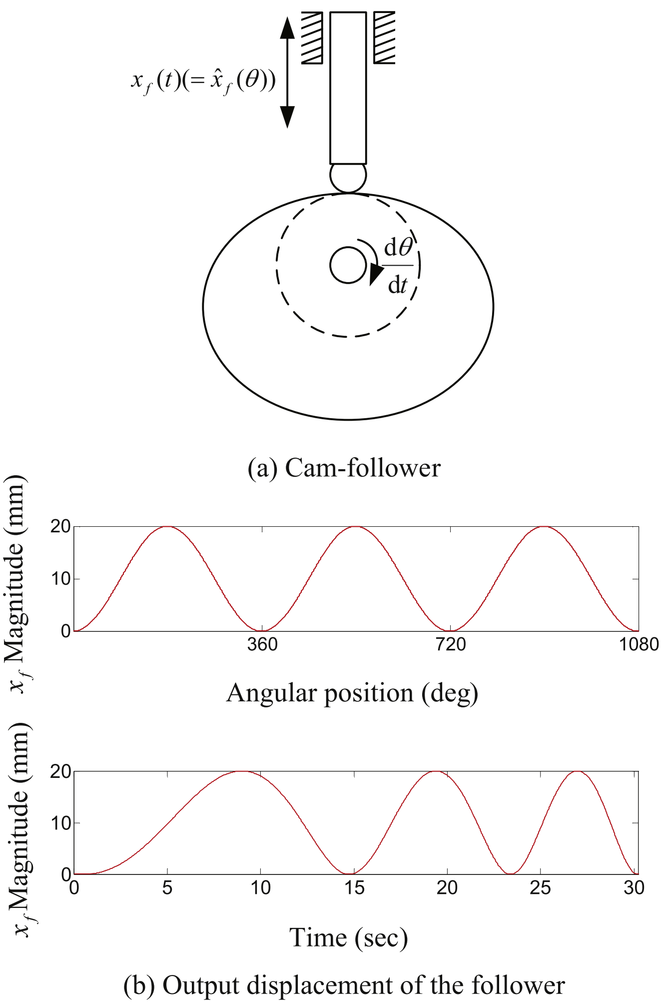

Fig. 1. Cam-follower and its output displacement.

Kim, 1995; Pipeleers, Demeulenaere, Schutter, & Swevers, 2008; Steinbush, 2002). Employing a coordinate transformation with respect to the angular position, Chen and Yang proposed a reduced-order adaptive repetitive controller for uncertain variable-velocity motion systems, where the original linear time-invariant system is reformulated under a generic spatial sampling strategy which results in a nonlinear system in the spatial domain so that feedback linearization is needed (Chen & Yang, 2009; Yang & Chen, 2012, 2011). The proposal is feasible theoretically, however, there are many technical issues in its implementation. A feasible and practical method, both from a theoretical as well as a technical point of view, is presented by Yao, Tsai, and Yamamoto (2013) which utilizes the angular position to manipulate the delayed data and an interpolation scheme to properly access data in the buffer memory. Nevertheless, both the storage and the calculation are increased and the process gets more complicated. In these repetitive control schemes, the core is an internal model.

Besides position-based periodic disturbances, there also exist other uncertain disturbances and unknown dynamics in rotary machines whose properties are hard to model. Recently, active disturbance rejection control (ADRC) has been well developed to achieve a satisfactory performance for uncertain systems, which is symbolized by the use of extended state observer (ESO). This method has found far-ranging applications in many theoretical works and practical projects (Frank, Zheng, & Gao, 2012; Han, 2009; Huang, Xue, & Gao, 2014; Talole, Kolhe, & Phadke, 2010; Wu & Chen, 2009; Xia, Zhu, Fu, & Wang, 2011; Zheng, Chen, & Gao, 2009). ADRC emphasizes on estimating and compensating for the total disturbance or total uncertainty, coupled with the states of the system, which lumps the effects on the output stemming from both external disturbance and unknown dynamics. Moreover, some valuable state information can be obtained with ESO such as the angular velocity of a rotary machine, which may save the computational resources.

In this paper, a digitally controlled continuously rotary machine is considered, i.e., the testing table system which is used to test and calibrate inertial components. The command of angular velocity of the system varies in a wide range in order to achieve continuous test. So, disturbances existing in the system are mostly periodic in terms of the angular position. This means that the traditional time-domain internal model scheme is not applicable. Motivated by the discussion above, an approach of spatial internal model is proposed for this kind of systems. A specific method using the angular position is developed to construct the corresponding control signal. Moreover, an linear extended state observer (LESO) with a simpler structure than typical ESO is constructed to estimate the uncertain disturbances and dynamics acting on the testing table system, which simplifies the parameter tuning and implementation significantly. Combination of these two elements leads to a compound control method where the angular velocity used in the spatial internal model is estimated by the LESO.

Further, the proposed compound control approach is applied to the practical rotary machine which is implemented under uniform time sampling. For an angular velocity servo-system implemented by a strategy of angular position-based feedback control, the steady state error relevant with the angular velocity command is inevitable in the classical time-invariant controls. However, the introduced LESO solves this problem to a great extent.

The rest of the paper is organized as follows. In Section 2, an angular position feedback control testing table system is reviewed, the disturbances to the plant are analyzed in the time domain and the angular position domain, respectively. The compound control scheme is presented in Section 3. Section 4 presents some specific methods and remarks aiming at parameter tuning of the compound controller. Comparisons and experimental studies are illustrated in Section 5 to validate the proposed approach. Section 6 summarizes the paper.

2. Analysis of testing table

In this section, the testing table is modeled by a frequency sweeping operation on the plant, and the disturbances acting on the system are investigated from a frequency spectrum analysis point of view.

2.1. Experimental modeling of plant

The block diagram of the closed-loop system is shown in Fig. 2, where the plant $P(s)$ is a third-order system which includes an integrator owing to the structure of angular position feedback. r and y are the reference input and angular position respectively. So, e denotes the tracking error between r and y. The control input u is synthesized by a dynamic controller $K(s)$ and there is a disturbance d acting on $P(s)$.

Identification experiments are carried out in an open loop manner. A sinusoidal signal u is imposed on the plant and the angular position output y is measured by a photoelectric encoder. By changing the frequency of u, sequences of gain and phase are obtained as shown by the "+" in Fig. 3. Then, the plant model