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Speed tracking control of pneumatic motor servo systems using observation-based adaptive dynamic sliding-mode control

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ABSTRACT

This study aims to develop an adaptive high-precision control system for controlling the speed of a vane-type air motor (VAM) pneumatic servo system. In practice, the rotor speed of a VAM depends on the input mass air flow, which can be controlled by the effective orifice area (EOA) of an electronic throttle valve (ETV). As the control variable of a second-order pneumatic system is the integral of the EOA, an observation-based adaptive dynamic sliding-mode control (ADSMC) system is proposed to derive the differential of the control variable, namely, the EOA control signal. In the ADSMC system, a proportional–integral–derivative fuzzy neural network (PIDFNN) observer is used to achieve an ideal dynamic sliding-mode control (DSMC), and a supervisor compensator is designed to eliminate the approximation error. As a result, the ADSMC incorporates the robustness of a DSMC and the online learning ability of a PIDFNN. To ensure the convergence of the tracking error, a Lyapunov-based analytical method is employed to obtain the adaptive algorithms required to tune the control parameters of the online ADSMC system. Finally, our experimental results demonstrate the precision and robustness of the ADSMC system for highly nonlinear and time-varying VAM pneumatic servo systems.

1. Introduction

Renewable energy sources have recently attracted a lot of attention because of increasing environmental concerns and stringent laws for regulating the use of non-renewable energy sources. As a result, compressed air energy has found applications in a number of industrial areas such as manufacturing, transportation, automation, and bionics because of the advantages of this energy source such as zero pollutant-emission, simple structure, and outstanding control performance [1]. To convert pneumatic energy into mechanical motion, various pneumatic drives have been used in different areas such as actuator systems [3,4], servo systems [5,6], locomotives brake [7], manipulator [8], beams system [9], and artificial muscles [10]. Unlike electric or hydraulic actuators, servo pneumatic actuators are characterized by their clear usage, simple maintenance, easy implementation, low cost, and high power density. In addition, servo pneumatic actuators are able to reduce the possibility of electrical shocks or fires occurring in high temperature, flammable, or explosive operational environments. The demand for high-accuracy air motor systems that can be used in industrial applications has increased in recent years, and numerous scientists have started using servo-controlled pneumatic air motors to develop complicated motion control tasks [11–16].

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System modeling and dynamic analysis are crucial for accurately predicting system behavior and efficiently designing control strategies. In one study, linear and rotary pneumatic actuators were developed [3], and two pneumatic circuit formulas, *i.e.*, an air thermodynamic transformation equation and a corresponding energy equation, were derived using a bond graph approach. Other studies have proposed using scroll air motors as pneumatic actuators [17,18]. These studies reported a model developed on the basis of adiabatic processes and perfect gas assumptions. A control-oriented vane-type air motor (VAM) model was developed in another study and it used two basic elements; an isentropic nozzle and a control volume [19]. In this study, parameters such as temperature and pressure inside the chamber of the motor, speed and torque of the motor, and the mass air flow (MAF) rate of air consumption were simulated and experimentally verified in a detailed manner.

Pneumatic servo systems demonstrate highly nonlinear and time-varying behaviors because of the compressibility of air, friction of mechanical components, dead-zone effect of control valves, eccentric mechanisms, and aerodynamic forces [3–6]. These systems will yield different responses even with the same inlet MAF [13]. As such, the nonlinear characteristics of these systems make their control as challenging issues. A study developed and experimentally evaluated a proportional–integral (PI) position controller that can be used in a low-cost industrial pneumatic actuator [4]. A function approximation technique based adaptive controller has also been proposed for use in pneumatic servo systems with variable payload and uncertain disturbances [5]. Another study proposed using a state-feedback nonlinear controller for a pneumatic cylinder based on the theory of homogeneous, finite-time stable, ordinary differential equations [6]. One study proposed using a sliding-mode control (SMC) system with a non-linear disturbance observer to control a pneumatic muscle actuator that can be used in a hand rehabilitation device [10]. Another study considered using a neural network (NN)-based model-free controller to achieve high-accuracy speed control in a VAM [16]. In the present study, a novel adaptive control strategy, different from these aforementioned methods, has been developed.

Proportional–integral–derivative (PID) controllers are widely used in industries and academia. However, conventional PID controllers do not exhibit satisfactory control over highly nonlinear and time-varying systems because of their linear structures with constant control gains. To deal with this problem, various approaches were proposed to improve the control performances of the conventional PID or PI controllers. A general type-2 fuzzy logic sets and a modified harmony search algorithm were integrated to tune the proportional and integral gains of the PI controller adaptively [20]. Moreover, PID neural networks (PIDNN) [21] have been developed to tune the proportional, integral, and derivative gains of a PID controller online. Therefore, the PIDNN reinforces the traditional PID control with adaptiveness. On the other hand, a proportional–integral–derivative fuzzy neural network (PIDFNN), which builds upon the advantageous characteristics of the PIDNN and fuzzy neural network (FNN) [22], has been proposed [16]. Unlike conventional FNNs, the PIDFNN uses an auxiliary multi-input multi-output (MIMO) PIDNN within its architecture to perform adaptive PID control with online tuning fuzzy rules. Experimental results for the PIDFNN demonstrated better control and learning abilities than that demonstrated by traditional PID and PIDNN controllers.

SMC is a widely studied control approach that provides robustness against certain disturbances and system uncertainties [23–30]. However, the required switching function for the hitting control results in high-frequency chattering and leads to undesirable results such as low control accuracy and high wear of moving mechanical parts. Therefore, a variety of solutions have been proposed to suppress the chattering phenomenon [23–28]. Among these methods, dynamic SMC (DSMC) is an effective method for eliminating the chattering that has received a lot of attention in recent years [23]. Besides, the differential of the control signal can be obtained directly according to this design. However, the boundary for realizing the hitting control of a DSMC is always vague and changeable in a practical control system. On the other hand, some studies applied fuzzy approximation methods in the SMC in order to directly estimate the uncertainties to deal with the undesirable chattering phenomenon [24,25]. Furthermore, an optimal type II fuzzy SMC approach was presented to not only warranties the constancy and hardiness against uncertainties, but also considerably decreases the control chattering inherent in traditional SMC [26]. Another adaptive fractional order PID sliding mode controller (AFOPIDSMC) using a Bat algorithm was proposed to control a Caterpillar robot manipulator [27]. In the AFOPIDSMC, a new combined control law was developed for chattering reduction by means of fractional order PID controller and high trajectory tracking through using SMC. Additionally, an adaptive neural network integral SMC was proposed to control a biped robot [28]. To eliminate the chattering phenomena, an adaptive neural network was used to estimate the unknown disturbances of the robot directly.

In general, the control methods for the VAM type pneumatic servo systems can be majorly classified into two classes regarding the ways for deriving a control signal. The first class is the model-free control, such as fuzzy control [11] and PID control [15], in which the control systems are used to derive the control signals without knowing the exact model of the system. According to the control of the effective orifice area (EOA) of the electronic throttle valve (ETV), the speed of the VAM can be adjusted well under some specific operating conditions. Nevertheless, favorable control performance levels are guaranteed only under these conditions because the control strategies or algorithms encounter difficulties in considering all the operating situations in advance. Moreover, the robustness of the control systems are weak because the parameters of the controller are not adaptive. The second class is the model-based control such as backstepping control [13] and SMC [14]. These control systems assumed that the difference between the upstream and downstream pressures of the VAM is proportional to the EOA. Thus, the control systems are used to control the pressure difference for regulating the output torques directly, thereby changing the rotor speed. However, in practice, the EOA possesses a complicated one-order dynamic with respect to the pressure [2], rather than the simple proportional relation. Therefore, the control performance levels are restricted due to the omission of this one-order dynamic. Furthermore, considering the highly nonlinear and time-varying