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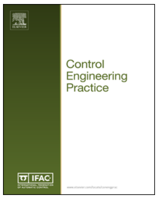

Backstepping dynamic surface control for an anti-skid braking system

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A R T I C L E I N F O

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A B S T R A C T

The electric aircraft landing system, as one of the important components of more electric aircraft (MEA) and all electric aircraft (AEA), has been a subject of interest in recent years. An anti-skid braking system (ABS), which is the crucial component of the electric aircraft landing system, has the function of regulating the wheel slip ratio such that the braking process operates in a stable state. In this paper, an approach that combines a nonlinear backstepping dynamic surface control (DSC) and an asymmetric barrier Lyapunov function (ABLF) is presented to not only track the reference slip ratio but also to avoid the slip ratio in the unstable region. We demonstrate that the proposed controller can guarantee the boundedness of the output constraints and the stability of the overall system. Using the ABLF allows one to relax the required initial conditions on the starting values of the wheel slip ratio and subsequently make the wheel slip constraints more flexible for various runway surfaces and runway transitions. The DSC is introduced to eliminate repeated differentiation resulting from ABLF synthesis, which can relax the restrictions on the high-order differentiability for stabilizing functions and the high power of wheel slip tracking error transformation. The proposed controller can avoid the negative effects of disturbance produced by repeated differentiation and can construct a simple controller for wheel slip control. The results of simulations with varying runway surfaces have validated the effectiveness of the proposed control scheme, in which the output constraints on the wheel slip ratio are guaranteed not to be violated and self-locking is avoided.

1. Introduction

“More electric aircraft” (MEA) and “all electric aircraft” (AEA) have emerged with promising advantages in terms of the best way to provide secondary power at low cost, improvements in enhanced reliability, easier maintenance, reduced on-board weight and increased safety. Technology of high-power-density electronics and control strategies creates a viable path, fueled by economic gains, for migrating many and potentially all powered systems toward electrically powered systems to achieve MEA or AEA (Bose, 2009; Jones, 1999). Although commercial aircraft landing systems are hydraulically driven, the electric landing system in aircraft has provided an opportunity to improve safety and efficiency with the goal of developing MEA and AEA during the past decades. For example, electronic control systems improve the accuracy and the ability to easily incorporate changes in design parameters, such as the steering rate and steering ratio in the steering system, and they help to overcome problems of leakages and fire hazards in actuation systems. The primary motivation behind this major change in braking system design can be attributed to the continuous modulation of electromagnetic braking torque generated by the electric motors during the braking process (Shemanske, 1983; Tanelli et al., 2008), which allows wheel slip control to be formulated as a classical regulation problem.

The aircraft electrical landing system is an important device that provides suspension during landing. An anti-skid braking system (ABS) is a mechanism in the landing system that protects against wheel skidding, which shortens the landing distance and landing time, thereby increasing landing security without sacrificing the directional stability and steerability of the aircraft. The objective of the ABS is to regulate the wheel slip ratio operating within the stable region of μ–λ characteristics. Some characteristics of aircraft landing systems, such as complex nonlinearity and model uncertainties in the high-order system, have produced difficulties in ABS control design, and many advanced control techniques have been widely applied to the ABS design. Among these methods, sliding-mode control is commonly used to reduce the dependency on a model (de Castro, Araujo, & Freitas, 2013; Harifi, Aghagolzadeh, Alizadeh, & Sadeghi, 2008; Lin & Hsu, 2003; Subudhi & Ge, 2012). Moreover, a class of fuzzy/neural network controls and their combination with adaptive approaches (Ćirović

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& Aleksendrić, 2013; Mirzaei et al., 2005; Sharkawy, 2010) have been used for adaptive prediction of wheel slip. In addition, feedback control (Mirzaeinejad & Mirzaei, 2010; Tanelli et al., 2008), iterative learning control (Mi, Lin, & Zhang, 2005) and extremum seeking control (Dincmen & Güvenc, 2012; Dincmen et al., 2014; Zhang & Ordóñez, 2007) are applied in this field. Many research efforts have been devoted to adjusting the setting of slip ratio and regulating the reference slip ratio or optimal slip ratio to achieve good tracking. However, wheel slip control with output constraints has rarely been addressed.

It is clear that the wheels of an aircraft might lock with any further increase of the wheel slip beyond its optimum value while the tire-runway friction falls to its sliding value, consequently inducing uncontrollable motion because the lateral force is reduced to almost zero; thus, the aircraft might lose control and directional stability. In addition, it might induce severe damage to the aircraft and injury to the passengers in a short amount of time. Thus, the basic objective of ABS is to regulate wheel longitudinal slip at its optimum value while maximizing longitudinal tire-runway friction to generate large lateral force. Moreover, the wheel slip should not be violated within a range and correspondingly should only operate within the stable region of μ–λ characteristics. Therefore, it is important to address the output constraints on the wheel slip ratio to guarantee bounded control action for achieving a more efficient and robust aircraft braking system.

The barrier Lyapunov function (BLF) and its variants have been widely applied to state constraint and output constraint problems (Niu & Zhao, 2013; Ren et al., 2010; Tee et al., 2009, 2011) for nonlinear systems in Brunovsky form (Ngo, Mahony, & Jiang, 2005) using the backstepping technique (Krstic, Kanellakopoulos, & Kokotovic, 1995). With these approaches, good tracking performance without violation of any constraints has been achieved. However, the difficulty in eliminating repeated differentiation of certain nonlinear controllers in backstepping has drastically increased the problem of 'explosion of complexity' (Wang & Huang, 2005) as the order n of the system increases. For example, m and p in the stabilizing function and the output tracking error transformation involved in asymmetric barrier Laypunov function (ABLF) synthesis must be chosen as $p \geq 2n$ and $m \geq \max\{3, n\}$, respectively, to ensure that the control law is continuously differentiable in the working region (Tee et al., 2009), which can produce severe proliferation and singularity for the system. Consequently, it can result in slow convergence and unstable performance in real situations. Dynamic surface control (DSC) (Swaroop, Hedrick, Yip, & Gerdes, 2000) is employed to eliminate this problem by utilizing a first-order filter to the synthetic input at each step of the recursive backstepping procedure.

Table 1
Parameters for the aircraft model.

Name	Description
m	Weight of aircraft
V_x	Longitudinal velocity of aircraft
T_0	Engine thrust force in idle state
F_x	Aerodynamic drag
F_y	Aerodynamic lift
F_s	Parachute drag
F_f	Braking friction force between tire and ground
N_1	Main wheel support force
N_2	Front wheel support force
n	Number of main wheels
h_c	Center of gravity height
h_s	Distance between parachute drag line and center of gravity
h_t	Distance between engine force line and center of gravity
a	Distance between main wheel and center of gravity
b	Distance between front wheel and center of gravity
ρ	Air density
C_x	Aerodynamic drag coefficient
C_y	Aerodynamic lift coefficient
C_{sx}	Parachute drag coefficient
S_x	Aerodynamic drag coefficient
S_y	Aerodynamic lift coefficient
S_{sx}	Parachute area
k_t	Velocity coefficient of engine
T_{0_ini}	The initial engine force in idle state

In addition, electrical motors are important components in an electrical drive system, in which aerospace applications place specific stringent requirements (from standards, regulations and a set of codes) for reliability and power density on the electrical machine employed (Boglietti, Cavagnino, Tenconi, & Vaschetto, 2009; Cao, Mecrow, Atkinson, Bennett, & Atkinson, 2012). The brushless DC motor has the advantages of simpler control and less onerous sensing requirements, as well as the potential to provide high power density, which make brushless DC motor drives strong candidates for aerospace applications. In this paper, we study the use of the brushless DC motor drive as an actuator, which makes the aircraft electric braking actuation system a high-order system.

Motivated by the existing methods, we propose backstepping DSC based on ABLF to address nonlinear wheel slip control with output constraints to avoid self-locking and to achieve zero steady-state error tracking performance of the optimum slip ratio. The remainder of this paper is organized as follows. The aircraft landing system and the actuator dynamics are described and discussed in Section 2. Section 3 formulates the barrier Lyapunov function problem. In Section 4, we derive the control scheme and demonstrate its stability. The control scheme for wheel slip control is evaluated through a simulation study in Section 5. We conclude this paper in the last section.

2. System dynamics

An accurate model of an aircraft has been constructed as a control test bed from the moment that the aircraft reaches the ground to the moment that the aircraft has decreased to a taxiing velocity. This model includes a model of the aircraft aerodynamics coupled with the wheel model, ground-contact friction model with varying runway surfaces and actuator model of the brushless DC motor.

2.1. Aircraft landing system dynamics

The aircraft is considered to be a rigid body with mass gravity localized in the center of gravity, and the landing gear strut is also considered to be rigid. In addition, the aircraft should maintain the correct heading when it is taxiing under asymmetric loads, such as cross-wind landing, one side main wheel bursting, and one side main wheel brake failure. Then, the aircraft is assumed to be symmetric about the xz plane, in which the lateral, vertical and tire deformations are neglected. Furthermore, the crosswind effect and earth curvature are also neglected (Papadopoulos, Self, & Kapadoukas, 1998).

Under these assumptions, a simplified dynamic model of aircraft is described by the interactions of forces as Eq. (1) (parameters described in Table 1), as shown in Fig. 1, which is loaded by the aerodynamic forces and moments (F_x, F_y, $N_1 a$ and $N_2 b$), engine thrust force and moment (T_0 and $T_0 h_t$), and landing gear response forces and moments (F_s, F_f, $F_s h_s$ and $F_f h_c$). The different forces and moments are calculated in separate functions as Eq. (2), where the aerodynamic coefficients (described in Table 1) can be found from the look-up tables in Hanke and Nordwall (1970). Subsequently, the terms are entered into Eq. (1)