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Position tracking control of a helicopter in ground effect using nonlinear disturbance observer-based incremental backstepping approach

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ABSTRACT

Helicopters are highly nonlinear and internally unstable air vehicles, the dynamic response of which can be strongly influenced by flight conditions (wind gust, ground effect, etc.). Therefore, it is a challenging task to design a reliable flight control system (FCS) with all safety and performance requirements satisfied. This paper investigates the robust position tracking problem of a helicopter in ground effect (IGE). Based on a highly reliable and computational efficient finite state representation of rotor flow field IGE, a novel nonlinear disturbance observer-based incremental backstepping (NDOIBS) controller is designed to track position commands (all derivatives of the reference trajectory are known) under the influence of system uncertainties and external disturbances. Without requiring the exact knowledge of helicopter dynamics, the NDOIBS approach guarantees that instant control increments are derived in terms of Lyapunov theory and ensures robustness in the presence of mismatched disturbances whose first derivatives are bounded. It is shown that all state variables of the closed-loop system are semi-globally uniformly ultimately bounded (SGUUB). In addition, to further improve the horizontal position tracking performance, rotor state feedback (RSF) technique and a disturbance feedback strategy are applied to develop a pitch stability augmentation system (SAS). Finally, controller performance is demonstrated through numerical simulations using the Bo-105 utility helicopter. With the efficiency and robustness properties verified, the suggested NDOIBS control scheme shows great potential for implementing advanced FCS designs in existing helicopters.

1. Introduction

Generally, helicopters are reliable and efficient air vehicles, capable of executing various missions in both civil and military. Compared with fixed-wing aircrafts, helicopters are more suitable for performing near-ground operations due to their unique characteristics of maneuverability and low-speed performance.

For a helicopter operating in the proximity of ground surface, ground effect commonly occurs when the height of a helicopter is smaller than one rotor radius. The presence of the ground reduces the downward induced velocity at the rotor disk, and therefore, the lifting capacity of the main rotor increases. However, the aerodynamic impact of ground effect is intended to deteriorate helicopter's stability, in that the reflected airstream causes unexpected thrust variations. Furthermore, helicopter operation IGE addresses significant challenges for flight control, such as take-off against rapidly decreased uplifts, landing with low-impact approaching speed and maintaining steady hover in degraded visual environment. Therefore, the influence of ground effect has to be considered in the FCS design, and controller robustness to external perturbations should be enforced.

Before proposing a reliable FCS design, it's essential to understand the flow field, aerodynamic forces and moments of rotating blades. An accurate description of such results can be obtained through Computational Fluid Dynamics (CFD) method [1–3], but it might take a great amount of computational effort. For the purpose of FCS design, it is appropriate to construct a simulation model that can be selected for real-time use. Among various methodologies proposed for rotor wake analysis, the finite state modeling approach [4] enjoys great advantages in real-time simulation, because it allows a state-space representation based on which the system stability can be analyzed and flight control laws may be derived. Previous finite state representations [5,6] are used to predict the induced flow field either on or above the rotor disk. While in re-

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cent years, applying the adjoint theorem [7] and blending method [8,9], the developed state-space model is capable to give exact solutions of the axial induced velocity everywhere in the flow field.

With the accuracy and robustness of the finite state inflow model greatly improved, the finite state modeling technique can be applied to describe the rotor inflow of a helicopter in ground effect. Two approaches are commonly applied to simulate ground effect. One is to use an image rotor [10] and the other is to place a ground rotor in the system. For both approaches, the boundary condition that no flux goes through such a non-penetrable surface should be satisfied. However, it is shown that the former approach is considerably limited in practical implementations [11]. Utilizing the ground rotor scheme, Hong et al. [12] developed the Peters–He model by representing the influence of the ground surface as a source-type pressure perturbation in the flow field, while Yu and Peters [11] extended the Morillo dynamic wake model to propose a three-dimensional state-space formulation of ground effect, which was tested in both steady and dynamic states.

As demonstrated in [11,12], the aerodynamic nature of ground effect is unsteady and highly nonlinear, which makes the design of a helicopter FCS challenging. At present, there have been limited analysis dedicated to controller designs of a helicopter operating in ground effect, and the relevant control approaches include adaptive backstepping [13,14], sliding mode control [15], LQR [16,17], H_2 state feedback control [18] and H_∞ state feedback control [19]. Although simulation experiments verified the effectiveness of the proposed control approaches, several problems with these studies are summarized as follows:

1) Most controller designs require that the rotorcraft dynamics should be affine in controls, which is not suitable for the large-scale helicopter due to its aerodynamic nature of thrust generation.

2) Conservatism is introduced by modeling helicopter dynamics as linear systems that are described by stability derivatives, because the assumption of small deviations from nominal conditions cannot be strictly satisfied.

3) The time-varying and distributed nature of rotor inflow IGE cannot be captured accurately by using either the Cheeseman and Bennett empirical model or the parametric representation of experimental data, and the resulted model inaccuracies would lead to compromised controller performances.

To deal with these drawbacks, the newly developed nonlinear incremental control scheme would probably provide more insight on controlling non-affine, highly coupled, strong nonlinear helicopter systems than other existing nonlinear control approaches [20]. One of the most representative incremental control methods is Incremental Nonlinear Dynamic Inversion (INDI) [21–23], which reduces controller dependency on the complete vehicle model. This control policy uses state accelerations as feedback signals to better eliminate sensitivity to matched disturbances, and the increments of control commands are calculated to solve the problem of systems not being control affine.

After recent years' development of the INDI methodology, many achievements have been utilized to solve flight control problems of fixed-wing aircraft [24], unmanned tiltrotor [25], quardrotor [26] and spacecraft [27]. Moreover, great interests are aroused in applying the INDI method for controlling helicopters. In [28], a 6-axis INDI-based autopilot was tested by performing various maneuvers advised in the ADS-33 standard, and three adaptations of the INDI approach were proposed to upgrade the Apache's legacy flight control law [29].

INDI is an implicit control method because the explicit cancellation of nonlinearities is not exhibited. Besides, the closed-loop response doesn't follow an explicit model but depends on the linear controller designed for the outer loop, which means that the stability and robustness of the INDI scheme cannot be rigorously proved. For this consideration, Acquatella [30] developed the incremental control framework via applying the Lyapunov-based backstepping procedure. By investigating the convergence property in terms of the Lyapunov stability framework, the incremental backstepping (IBS) approach gives an advantage on illustrating the closed-loop response in the presence of parameter variations and model uncertainties [31]. Furthermore, the IBS flight control law was already tested through in-flight experiments [32], demonstrating that this approach is practically available for implementing advanced FCS designs.

The nonlinear incremental control scheme ensures desired robustness properties against matched disturbances. However, it exhibits unfavorable disturbance rejection capabilities in accounting for mismatched disturbances, especially those that don't explicitly reside in the channels of control inputs. Until now, little work has been proposed to study the disturbance rejection problem of a helicopter in the presence of mismatched disturbances using the incremental control policy. On the other hand, due to the difficulty of describing rotor inflow IGE, few studies have proposed reliable FCS designs based on a real-time simulation model of ground effect.

In this research, we attempt to investigate the robust position tracking problem of a helicopter in ground effect where mismatched disturbances and system uncertainties are considered. The main contributions of this paper are summarized as follows:

1) This paper appears to be the first result dedicated to designing nonlinear incremental control laws based on a reliable finite state representation of rotor inflow IGE. With the rigorous solution of the induced velocity obtained, instantaneous rotor loads that are computed through transient flow field on the rotor disk can be applied for incremental control law design, which addresses an integrated scheme of the controller design and helicopter dynamic model.

2) A novel nonlinear disturbance observer-based incremental backstepping control methodology is designed to attenuate unfavorable impacts of mismatched disturbances and it guarantees that the closed-loop system is stable in the sense of SGUUB. Moreover, the proposed flight control architecture is applied to solve position tracking problem of a helicopter operating in ground effect.

The rest of this paper is organized as follows. Section 2 introduces the helicopter mathematical model, including the blade flapping motions, rigid body dynamics and the potential flow inflow model. Section 3 mainly illustrates the proposed NDOIBS control methodology, its stability analysis and application to helicopter position control. The nominal performance and robustness tests are presented in Section 4. Finally, the conclusions are drawn in Section 5.

2. Helicopter dynamic model

2.1. Blade flapping model

The fundamental aerodynamic characteristics of the main rotor primarily depend on the blade motions. Flapping, lagging and feathering are three basic motions of a rotating blade. Actually, the flap motion of rotor blades contributes most to the tilting of the rotor disk.

For the qth blade of a lifting rotor subject to aerodynamic loading, the rigid blade flapping equation is expressed as

$$I_\beta \ddot{\beta}_q + \left(\Omega^2 I_\beta + K_\beta\right)\beta_q = \int_0^R L_q r dr \tag{1}$$

where I_β and K_β are the moment of inertia and elastic coefficient of the root spring for the qth blade, R and Ω the rotor radius and rotor rotational speed, β_q the flap angle of the qth blade, r the radial location on the blade, measured from the center of rotation to