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Research article

Trajectory tracking for two-degree of freedom helicopter system using a controller-disturbance observer integrated design

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A B S T R A C T

Trajectory tracking control for helicopters, which are widely used in severe situations such as military and rescue missions, is a challenging field of research. In helicopter system, the stability problem and predefined trajectories tracking are main challenges, especially in the presence of external disturbances and dynamic model uncertainties. Hence, a robust control design is needed for tracking the desired references. There has been a lot of motivation for solving these problems with simpler methods and also reducing the couplings in the helicopter system to achieve better performance, as the presented paper attempts to fill these gaps. This paper focuses on designing control laws for two-degree of freedom helicopter system while assuring the closed-loop stability. A nonlinear disturbance observer-based control (NDOBC) is designed for attenuating the effects of exogenous disturbances. Trajectory tracking controller and nonlinear disturbance observer are formulated in the form of two linear matrix inequality (LMI) problems. The closed-loop system stability, including controller and observer, is investigated by Lyapunov theorem. The effectiveness of the proposed design for tracking the trajectories (vertical flight and pitch angle rotor blade) and disturbance estimation is verified by simulation results.

1. Introduction

Helicopter is a well-known aircraft which has been widely used in many applications. The helicopter motion behavior seems to be a challenging research topic, due to its wide usage in severe situations. The researches on helicopter have been focused on two important issues: the attitude control and the vertical flight control [1–4]. Choosing an accurate mathematical model is a challenge for the controller design. All the proposed models have a special degree of freedom which shows the accuracy level of the modeling [5,6]. In this paper, a model with two-degree of freedom [7,8], which is defined as the altitude of helicopter and the collective pitch angle of rotor blade, is used. Tracking of the references, i.e., vertical flight and the blade pitch angle, is the main aim of the controller design.

Helicopter system is a multiple input multiple output (MIMO) system, including coupling terms with nonlinear behavior [9]. Some nonlinear controllers have been proposed to control for this system. In spite of appropriate dynamic characteristics, the proposed controllers may suffer from instability and weak maneuverability problems. In addition, in the helicopter system, presence of external disturbances may lead to undesirable performance [10]. Hence, a robust control design is needed for tracking the desired references.

Several control methods have been proposed in the literature for the tracking issue, including back-stepping, nonlinear dynamic inversion, model predictive control (MPC), H_∞, sliding mode control (SMC), adaptive neural network control and closed-loop optimal fuzzy reasoning [1,11–17]. Back-stepping control has been used to deal with the uncertainties of the dynamic model [17]. The SMC strategy has the ability to tackle any types of exogenous disturbances [18,19]. In Ref. [20], a discrete optimal control law is used to stabilize the quadrotor platform using a minimum amount of energy. This method can be applied for any flying vehicle. Adaptive back-stepping approach has been used for tracking of vertical flight and pitch angle references, in the presence of aerodynamic uncertainties and external disturbances [20,21]. According to the results, a significant tracking error is reported, without adaptation. The nonlinear disturbance observer-based control (NDOBC) can be applied to deal with the destructive effects of the uncertainties and external disturbances [22]. Based on this control method, it is possible to estimate them by an observer system. Moreover, for decreasing the tracking error and having a suitable performance, it

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Notations related to subspace

$\mathbb{R}$	set of all real numbers
$\mathbb{R}^n$	set of all real vectors of dimension n
$\mathbb{R}^{m\times n}$	set of all real matrices of dimension $m \times n$

Notations related to vectors and matrices

I_n	identity matrix of order n
A^{-1}	inverse matrix of matrix A
A^T	transpose of matrix A
$A>0$	A is Hermite (symmetric) positive definite
$A\geq 0$	A is Hermite (symmetric) semi-positive definite
$A>B$	$A-B>0$
$A\geq B$	$A-B\geq 0$
$A<0$	A is Hermite (symmetric) negative definite
$A\leq 0$	A is Hermite (symmetric) semi-negative definite
$A<B$	$A-B<0$
$A\leq B$	$A-B\leq 0$
$Tr(A)$	trace of matrix A
$\lambda(A)$	set of all eigenvalues of matrix A
$\lambda_{max}(A)$	maximum eigenvalue of matrix A
$\lambda_{min}(A)$	minimum eigenvalue of matrix A
$\|\|A\|\|$	spectral norm of matrix A
$\dot{x}(t)$	first-order derivative of vector x with respecttive to t
$\ddot{x}(t)$	second-order derivative of vector x with respecttive to t
$\dddot{x}(t)$	third-order derivative of vector x with respecttive to t
$A=B$	the equivalent relation between matrices A and B

Notations of relations and manipulations

$\in$	belong to
$s.\ t.$	subject to

Other notations

$diag$	$diag(d_1, d_2, \ldots, d_n)$ respects the diagonal

is necessary to design a proper controller in the closed-loop system.

In general, the main challenge of using nonlinear methods is the performance of responses to the control inputs. Methods, such as adaptive, adaptive back-stepping and conventional robust methods (like H_∞ or sliding mode) are mainly concerned about closed-loop stability of the system or reducing the effects of uncertainties and disturbances [22–24]. Generally, adaptive or adaptive back-stepping methods are not effective due to unavoidable uncertainties and disturbances that lead to steady-state errors in the helicopter system. Different robust methods have been investigated in the literature to overcome the uncertainties and disturbances [13,24,25]. These conventional methods usually impose heavy computational burden and in most cases cannot guarantee selection of optimal design parameters. These methods also have less concern about the issue of controller's performance to achieve desired responses. In the present paper, the authors tried to address this challenge, unlike other methods which basically deal with the stability or robustness of a nonlinear system [26]. The proposed method, due to its specific structure, has the capability to reach the desired characteristics of the transient response, including the settling time and overshoot; and it is also easy to control the steady state error in the responses. Moreover, combining the method with a disturbance observer offers more degrees of freedom to reduce the destructive effects of external disturbances imposed on the helicopter system.

Basically, reducing the destructive effects of uncertainties is a difficult task in the helicopter system due to its nonlinear nature and coupled terms (including coupling of system states with the inputs and with other states). The state decoupling approach separates the helicopter system into two single input single output (SISO) systems, but still some couplings (due to inputs) will be remained in the model [27]. An alternative solution to deal with the abovementioned problems is the sliding mode control. However, chattering will be observed in the control signals which is not desirable in practical applications. In sliding mode control, chattering issue has been of great importance and even combined methods, such as disturbance observer-based sliding mode control, has been used to overcome this problem [13].

There has been a lot of motivation for solving these problems with simpler methods and also reducing the couplings in the helicopter system to achieve better performance, as the presented paper attempts to fill these gaps. In other words, the authors' main motivation is to focus on the performance of responses and estimating the uncertainties in the helicopter system. The proposed method can solve these problems by separating the MIMO system into multi-SISO systems based on dynamic inversion uncoupling linearization approach and estimating uncertainties and disturbances with a novel disturbance observer. The proposed method is capable of being used for other helicopter system models as well as other nonlinear systems that are affected by uncertainties or disturbances.

In this paper, a new controller is proposed for robust tracking and an NDOBC approach is used for estimating external disturbances, simultaneously. The use of such a controller has never been seen in the literature. In particular, the controller coefficients are independent of the disturbance observer parameter which leads to minimize the tracking errors. A suitable dynamic structure is proposed for designing the nonlinear disturbance observer, and this kind of disturbance observer has never been used before. The main advantage of this observer is its capability to estimate the disturbances which have bounded derivatives. To gain the robust control laws, in the error dynamic equations two large value terms should be determined by solving the LMI problems. Due to presence of NDOBC in the closed-loop system, it is necessary to investigate the stability of the system using Lyapunov theorem. This will impose a number of additional constraints to the LMI problems.

The authors believe that this article is interesting in three main aspects: first, the design of a controller based on tracking error derivatives that has been rarely investigated, Second, disturbance rejection by solving an optimization problem that ultimately leads to better performance in reference tracking and third, presenting a new structure of disturbance observer which is able to estimate disturbances with bounded derivatives.

The rest of this paper is organized as follows: in Section 2, a MIMO helicopter model including coupled terms is introduced. In Section 3, a decoupling approach based on feedback linearization has been employed to convert the MIMO helicopter system into two separate SISO systems. Section 4 is dedicated to introduce the proposed controller for tracking in form of LMI problems. The closed-loop stability is proved and the robust control laws are obtained in Section 5. Simulation results are presented to verify the validity and effectiveness of the proposed method in Section 6. Finally, Section 7 draws the conclusions.

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