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A general method for closed-loop inverse simulation of helicopter maneuver flight

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Abstract Maneuverability is a key factor to determine whether a helicopter could finish certain flight missions successfully or not. Inverse simulation is commonly used to calculate the pilot controls of a helicopter to complete a certain kind of maneuver flight and to assess its maneuverability. A general method for inverse simulation of maneuver flight for helicopters with the flight control system online is developed in this paper. A general mathematical describing function is established to provide mathematical descriptions of different kinds of maneuvers. A comprehensive control solver based on the optimal linear quadratic regulator theory is developed to calculate the pilot controls of different maneuvers. The coupling problem between pilot controls and flight control system outputs is well solved by taking the flight control system model into the control solver. Inverse simulation of three different kinds of maneuvers with different agility requirements defined in the ADS-33E-PRF is implemented based on the developed method for a UH-60 helicopter. The results show that the method developed in this paper can solve the closed-loop inverse simulation problem of helicopter maneuver flight with high reliability as well as efficiency.

1. Introduction

A helicopter is a special aircraft which can perform hover, vertical takeoff and landing as well as low-speed maneuver flight. However, it is also an aircraft that is difficult to fly due to its unstable and heavy coupling characteristics, and this problem will be more severe during maneuver flight. Therefore, relevant topics on helicopter maneuver flight such as how to assess the maneuverability of a helicopter, how to find a best control strategy for certain maneuver, etc. need to be studied. At the early stage, maneuverability was not considered in helicopter design, and the only standard for helicopter design is performance. This situation lasted for decades until the first flying quality specification for rotorcraft appeared in 1961.[1] In the first flying quality specification, the MIL-H-8501A, various flying quality criteria such as control stick force, acceleration to stick input, etc. were proposed, and some of these criteria have obvious influences on helicopter maneuverability. Currently, the state-of-art flying quality specification for rotorcraft is

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the ADS-33E-PRF,[2] in which maneuverability is described more explicitly. There are totally 23 mission task elements (MTEs) defined in the ADS-33E-PRF with different agility requirements, and the flying quality as well as the maneuverability of a certain type of helicopter can be assessed by performing these maneuvers.

A flight test is a direct way and the most accurate method to determine flying quality as well as maneuverability for helicopters. However, a flight test can only be performed very limited times, so it is usually used to obtain an assigned level of flying quality only. In order to get more information about maneuverability of helicopters, some researchers use ground flight simulators to do simulation flight experiments instead of real flight tests.[3,4] One of the key techniques of a flight simulator is the mathematical model of helicopters. A helicopter is a very complex system, so flight dynamics modeling is also complicated, and it will be more difficult to obtain an accurate flight dynamics model of a helicopter during maneuver flight. In order to solve this problem, there are a lot of research works carried out in this domain.[5–7] The advantage of using a flight simulator to study maneuverability is that a pilot can perform different kinds of maneuvers without considering the safety problem, which is quite useful to help finding the maximum maneuverability of a certain helicopter. On the other hand, the cost of a simulation flight test is much lower than that of a real flight test, so it can be performed much more times than the latter one. The deficiency of a simulation flight test is that it cannot tell a pilot how to control a helicopter to finish each maneuver, and it cannot be used to optimize the flight trajectory as well as the control strategy for different kinds of maneuvers. Inverse simulation was proposed then to deal with these problems.

Inverse simulation uses some mathematical tools to calculate the pilot control time history for certain maneuvers, and it does not need a real pilot during the simulation procedure. Therefore, the cost of inverse simulation is very low, and it can provide very useful information to a pilot when he/she conducts a simulated or real flight test for the same maneuver. One commonly used inverse simulation technique is an optimization based method,[8–13] which gives a prescribed flight path for a certain maneuver at first, then establishes a cost function related to the error between the calculated flight path and the prescribed one, and finally, pilot controls for the maneuver are obtained based on some optimization algorithms. In order to increase the efficiency and practicality of inverse simulation, some improved methods such as sensitivity analysis, and [12] trajectory optimiaztion,[13] were proposed. Although the optimization based method is quite useful and has been used in inverse simulation for decades, its deficiencies are also obvious. Firstly, the calculation efficiency is poor, because it requires several iterations at each time step during the whole maneuver, and typically there are about 100 time steps in 1 s simulation. Secondly, the numeric stability of the optimization procedure is also poor since the dynamic characteristics of a helicopter are very complex, and sometimes inverse simulation may fail due to the divergence of numerical optimization. Finally, the optimization based method requires a prescribed trajectory of the maneuver to implement the optimization calculation. However, a lot of maneuvers do not have explicit trajectories. Therefore, this kind of method cannot be used to solve the inverse simulation problems of all kinds of maneuvers. In order to consider the pilot behavior during the maneuver flight, there are some research works focused on pilot modeling;[14–16] however, pilot modeling is also a complicated problem, and the introduction of a pilot model makes it more difficult to obtain inverse simulation results. Therefore, only simple pilot models and simple maneuvers are implemented currently. In recent years, another inverse simulation technique based on automatic control theory[17,18] is developed to conquer the difficulties encountered in the optimization based method. In this kind of method, no optimization calculation is required, so there is no numeric stability problem, and the inverse simulation efficiency is increased considerably. On the other hand, this kind of method does not depend on the flight trajectory, which indicates that this kind of method can be used to inversely simulate a wider range of maneuvers. Although it has been proven effective, the automatic control based method still has many problems to be solved. Firstly, in the current technique, only several typical maneuvers are inversely simulated by using this kind of method, and there is no general inverse simulation scheme based on this kind of method for all kinds of maneuvers. Secondly, the flight control system is not considered in current approaches, and neglecting the influence of the flight control system will make inverse simulation results a bit unreasonable.

In order to solve the above difficulties, a general method based on the optimal control theory for the helicopter closed-loop inverse simulation problem is developed in this paper. The influence of the flight control system is considered in the developed method. Three different maneuvers with different agility requirements are implemented for a UH-60 helicopter with a flight control system online. The differences between the inverse simulation results with and without considering the flight control system's influence are also studied.

2. Flight dynamics model for inverse simulation

The helicopter is a nonlinear, unsteady, high-order system, which is extremely true in maneuver flight. In order to increase the confidence of inverse simulation results, a nonlinear flight dynamics model as shown in Eq. (1) is used.

$$\dot{\boldsymbol{y}} = \boldsymbol{f}(\boldsymbol{y}, \boldsymbol{u}, t) \tag{1}$$

where $\boldsymbol{u}$ is the control input vector, t is the time variable, $\boldsymbol{f}(\cdot)$ is a nonlinear function, and $\boldsymbol{y}$ is the state vector of the helicopter which can be expressed in a more detailed form as Eq. (2).

$$\boldsymbol{y} = [\boldsymbol{y}_B^T, \boldsymbol{y}_R^T, \boldsymbol{y}_W^T, \boldsymbol{y}_U^T, \boldsymbol{y}_E^T]^T \tag{2}$$

where $\boldsymbol{y}_B^T$ is the helicopter body state vector, $\boldsymbol{y}_R^T$ is the rotor state vector, $\boldsymbol{y}_W^T$ is the rotor wake vector composed of inflow variables as well as wake geometry and distortion variables, $\boldsymbol{y}_U^T$ is the unsteady aerodynamic force and dynamic stall vector, and $\boldsymbol{y}_E^T$ is the engine state vector.

Since the unsteady aerodynamic phenomenon, dynamic stall, and dynamic wake distortion are considered in this flight dynamics model, it can be used to simulate different kinds of helicopter maneuver flight with different agility. More detailed information about this flight dynamics model can be found in Ref. 2.