EFFICIENT METHOD FOR INVERSE SIMULATION OF HELICOPTER MANEUVER FLIGHT

Wu Wei, scorpio_nuaa@nuaa.edu.cn, Nanjing University of Aeronautics and Astronautics, China

Abstract

The maneuverability is a key factor to determine whether a helicopter could finish certain flight mission success-fully or not. The inverse simulation is commonly used to calculate the controls of a helicopter to complete certain kind of maneuver flight and to assess the maneuverability. A general method for inverse simulation of maneuver flight to helicopters with flight control system online is developed in this paper. A describing function is established to provide general 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 control solver. The 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

The helicopter is a special aircraft which can perform hover, vertical takeoff and landing as well as low speed maneuver flight. However, the helicopter is also an aircraft that 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 early stage, the 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 to helicopter maneuverability. Currently, the state-of-art flying quality specification for rotorcraft is the ADS-33E-PRF[2], in which the maneuverability is described more explicit. 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.

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

The 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. So the cost of inverse simulation is very low, and it can provide very useful information to the pilot when he doing simulated or real flight test for the same maneuver. One commonly used inverse simulation technique is an optimization based method[8-13], this kind of method gives a prescribed flight path for certain maneuver at first, then establishes a cost function related to the error between the calculated flight path and the prescribed one, and finally, the pilot controls for the maneuver are obtained based on some optimization algorithm. In order to increase the efficiency and practicality of inverse simulation, some improved method such as sensitivity analysis[12], trajectory optimiaztion[13] etc. were proposed. Although the optimization based method is quite useful and has been used in inverse simulation for decades, its deficiencies are also obvious. First, the calculation efficiency is poor, because it requires iterations at each time step during the whole maneuver. Second, the numeric stability of the optimization procedure is also poor due to the complex characteristics of the helicopter. 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 problem of all kinds of maneuvers. In order to consider the pilot behavior during the maneuver flight, there is some research works focusing on pilot modeling[14-16], however, the pilot modeling is also a complicated problem, and the introduction of pilot model makes it more difficult to obtain the 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 hand, this kind of method does not depend on flight trajectory, which indicate that this kind of method can be used to inverse simulate a wider range of maneuvers. Although it has been proven effective, the automatic control based method still has many problems to be solved. First, in the current technique, only several typical maneuvers are inverse simulated by using this kind of method, and there is no general inverse simulation scheme based on this kind of method to all kinds of maneuvers. Second, the flight control system is not considered in the current approaches, and the neglect of the influence of flight control system will make the 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 invers 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 flight control system online. The differences between the inverse simulation results with and without considering flight control system influence are also studied.

2. FLIGHT DYNAMICS MODEL FOR INVERSE SIMULATION

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

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

In which $\boldsymbol{u}$ is the control input vector, $\boldsymbol{f}(\bullet)$ is time variable, $\boldsymbol{y}$ is nonlinear function, and 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 com-posed of inflow variables as well as wake geometry and distortion variables, $\boldsymbol{y}_U^T$ is the unsteady aerodynamic force and dynamic stall vector, $\boldsymbol{y}_E^T$ is the engine state vector.

Since the unsteady aerodynamic phenomenon, the dynamic stall as well as dynamic wake distortion is considered in this flight dynamics model, it can be used to simulate different kinds of the helicopter maneuver flight with different agility. More detailed information of this flight dynamics model can be found in Ref. 7.

3. GENERAL METHOD FOR HELICOPTER CLOSED LOOP INVERSE SIMULATION

The general closed loop inverse simulation method can be divided into three parts: flight control system modeling, mathematical description of maneuvers and pilot control calculation.

3.1. Flight control system modeling

The closed loop inverse simulation requires the flight control system model with two different levels. The simulation model which composed of helicopter flight dynamics model and flight control system model requires a high level model. In this level, the flight control system model should be closed to the real flight control system as much as possible. The pilot control calculation requires a lower level of flight control system model, and in this level, the hardware characteristics such as filter, sensor and actuator dynamics etc. can be neglected, only the simplified control law is remained. This is because in this level the flight control system model is only used to calculate the closed loop stability matrix as well as the pilot control solver's coefficients.

In this paper, the real engineering flight control system model of an UH-60 helicopter which can be found in Ref. 19 is used as the high level model for inverse simulation purpose. The model is implemented in Matlab Simulink environment, and then compiled to a dynamic link library (dll) file for further use. Based on the real flight control system model, a simplified flight control law is obtained by neglecting all the filter, sensor and actuator transfer functions. Then the control law is transformed into a multi-input-multi-output (MIMO) feedback control form as Eq. (3) which has a very compact format.

(3) $$\boldsymbol{u}_f = \boldsymbol{K}_f \boldsymbol{x}$$

In which $\boldsymbol{u}_f$ is the flight control system output, $\boldsymbol{x}$ is the helicopter responses including airspeed, Eula angles and angular rates, $\boldsymbol{K}_f$ is the feedback coefficient matrix.

3.2. Mathematical description of maneuvers

The mathematical description of maneuvers is a key factor for implementing inverse simulation successfully. For most of the current methods, the mathematical description depends on detailed flight trajectory, so it is not possible to describe all kinds of maneuvers for these methods. In this paper, a general form of mathematical description function is established as Eq. (4).

(4) $$\boldsymbol{Des} = [H_d, \dot{H}_d, q_d, \theta_d, p_d, \varphi_d, r_d, \psi_d]^T = \boldsymbol{g}(\boldsymbol{K}_d, \boldsymbol{x}_d)$$

Where the description vector $\boldsymbol{Des}$ is consist of 8 description variables, H_d is altitude, $\dot{H}_d$ is the changing rate of altitude, p_d , q_d and r_d are roll rate, pitch rate and yaw rate respectively, φ_d , θ_d and ψ_d are roll angle, pitch angle and yaw angle respectively, $\boldsymbol{K}_d$ is description coefficients vector, and $\boldsymbol{x}_d$ is the selected state vector of helicopter for certain maneuver, $\boldsymbol{g}(\bullet)$ is mathematical description function.

The Eq. (4) is a general form for describing helicopter maneuver flight. It is not only applicable to maneuvers that have explicit flight trajectory, but to all kinds of maneuvers. Therefore, no matter what the maneuver is, it can be described by the 8 description variables. The function structure and elements of $\boldsymbol{g}(\bullet)$ for all kinds of maneuvers is also the same, and the only difference between each maneuver is the expression of this function. More detailed information of the description function will be discussed in the next section with specific maneuvers.

3.3. Pilot control calculation

The pilot control calculation is the final step for inverse simulation, and in order to avoid numeric optimization which may cause numeric problems, a direct computation based on automatic control theory is established in this paper. On the other hand, the flight control system model is used in the control solver design procedure in order to separate the pilot control from control system output during the maneuver flight.

The basic solution of pilot control for any maneuvers can be obtained by using Eq. (5).

(5) $$\boldsymbol{u}_p = \boldsymbol{K}_p(\boldsymbol{x}_p - \boldsymbol{Des}) + \boldsymbol{K}_I \boldsymbol{x}_I + \boldsymbol{K}_c \boldsymbol{x}_c$$

Where $\boldsymbol{u}_p = [\delta_{col}, \delta_{long,} \delta_{lat}, \delta_{ped}]^T$ is the pilot control input at cockpit. The elements in $\boldsymbol{u}_p$ represent the collective stick input, longitudinal stick input, lateral stick input and pedal input respectively. $\boldsymbol{x}_p$ is the helicopter state response vector for pilot control calculation, its elements is the same as description vector $\boldsymbol{Des}$. $\boldsymbol{x}_I$ is the integration vector which is used to increase the control solver's performance at steady state. $\boldsymbol{x}_c$ is the compensation vector used to eliminate control coupling problem of the helicopter. $\boldsymbol{K}_p$, $\boldsymbol{K}_I$ and $\boldsymbol{K}_c$ are relevant coefficient matrix, their expressions can be found in Eq. (6) ~ Eq. (8).

(6) $$\boldsymbol{K}_p = \begin{bmatrix} K_H & K_{Hdot} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & K_q & K_\theta & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & K_p & K_\varphi & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & K_r & K_\psi \end{bmatrix}$$

(7) $$\boldsymbol{K}_I = \begin{bmatrix} K_{HI} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & K_{\varphi I} & 0 \\ 0 & 0 & K_{\psi I} \end{bmatrix}$$

(8) $$\boldsymbol{K}_c = \begin{bmatrix} K_{\varphi H} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & K_{cp} \end{bmatrix}$$

Since the integration and compensation coefficients are relatively small, and it is not difficult to determine these coefficients based on engineering experiences, the $\boldsymbol{K}_I$ and $\boldsymbol{K}_c$ matrix are set manually for each maneuver. However, the $\boldsymbol{K}_p$ matrix is not so easy to obtain, and the values are changed for different maneuvers that have different initial states and agility requirements. On the other hand, the determination of $\boldsymbol{K}_p$ matrix should consider the influence of flight control system. Therefore, a comprehensive algorithm based on optimal quadratic regulator theory to calculate $\boldsymbol{K}_p$ matrix for each maneuver is developed as follows.

First, trim the helicopter at the initial steady flight state for each maneuver, then linearize the helicopter flight dynamics model in trim condition, and the standard state space model as shown in Eq. (9) is obtained. In order to consider the influence of flight control system in determining $\boldsymbol{K}_p$, a closed loop state space model is then established as shown in Eq. (10) by combing Eq. (9) and Eq. (3).

(9) $\dot{\boldsymbol{X}} = \boldsymbol{AX} + \boldsymbol{BU}$

(10) $\dot{\boldsymbol{X}} = (\boldsymbol{A} + \boldsymbol{BK}_f)\boldsymbol{X} + \boldsymbol{BU}$

Second, define a cost function based on optimal quadratic regulator theory as shown in Eq. (11), where $\boldsymbol{Q}$ and $\boldsymbol{R}$ are non-negative definite and positive definite symmetric matrix respectively. Then minimize the cost function to find a best feedback controller that has high control precision as well as minimum control power. In order to solve this optimization problem, assume the original closed loop stability matrix and control matrix in Eq. (10) are constant for one maneuver, and then the solution of the optimization problem can be found as Eq. (12). In which $\boldsymbol{P}$ is the solution of algebraic Riccati equation as shown in Eq. (13). There are many comprehensive tools to solve the Riccati equation, so it is easy to obtain $\boldsymbol{P}$.

(11) $J = \frac{1}{2}\int_0^{\infty}[\boldsymbol{X}^T(t)\boldsymbol{QX}(t) + \boldsymbol{U}^T(t)\boldsymbol{RU}(t)]dt$

(12) $\boldsymbol{U}^*(t) = -\boldsymbol{R}^{-1}\boldsymbol{B}^T\boldsymbol{PX}(t)$

(13) $\boldsymbol{P}(\boldsymbol{A} + \boldsymbol{BK}_f) + (\boldsymbol{A}^T + \boldsymbol{K}_f^T\boldsymbol{B}^T)\boldsymbol{P} - \boldsymbol{PBR}^{-1}\boldsymbol{B}^T\boldsymbol{P} + \boldsymbol{Q} = 0$

Finally, based on the Eq. (12), the optimal feedback coefficient matrix can be obtained by using Eq. (14). Then eliminate all the cross coupling control coefficients in $\boldsymbol{K}^*$, and a solution of $\boldsymbol{K}_p$ for certain maneuver is obtained.

(14) $\boldsymbol{K}^* = -\boldsymbol{R}^{-1}\boldsymbol{B}^T\boldsymbol{P}$

4. APPLICATIONS TO TYPICAL HELICOPTER MANEUVERS

The detailed inverse simulation procedure by using the developed method will be addressed in this section. In order to show the developed method is capable of solving any maneuver flight problems, three typical maneuvers defined in the ADS-33E-PRF with large differences in course pattern as well as agility requirements are calculated in this paper. These three maneuvers are pirouette, vertical remask and high Yo-Yo.

4.1. Pirouette

The pirouette maneuver is a high precision flight mission with moderate agility requirement. This maneuver starts from a steady hover condition, and then accomplishes a lateral translation around a circle while keeping the nose of the helicopter pointing ate the center of the circle. The maneuver will be terminated at hover condition over the start point. The main performance standards of desired level at good visual environment (GVE) are concluded in table 1.

Table 1 Desired performance of pirouette maneuver at GVE.

Performance	Requirement
• Maintain a selected reference point on the rotorcraft within ±X m of the circumference of the circle	3.048
• Maintain altitude within ±X m	0.9144
• Maintain heading so that the nose of the rotorcraft points at the center of the circle within ±X deg	10
• Complete the circle and arrive back over the start point within	45 sec

The first procedure of inverse simulation of this maneuver is to determine the mathematical description function $\boldsymbol{g}(\boldsymbol{K}_d, \boldsymbol{x}_d)$. The pirouette maneuver can be divided into 2 steps, the first step is lateral translation around the circle, and the second step is hover when finishing the maneuver. Therefore, there are also 2 different mathematical description functions for this maneuver, as shown in Eq. (15) and Eq. (16).

$$
\boldsymbol{g}_1^{pirouette}(\boldsymbol{K}_d, \boldsymbol{x}_d) = \begin{bmatrix} H_{com} \\ \dot{H} \\ q \\ K_u u + K_R (R_{com} - R) + \theta_{trim} \\ p \\ K_v (v_{com} - v) + \varphi_{trim} \\ \dfrac{180 v}{\pi R} \\ \arctan(\dfrac{Y_c - Y_h}{X_c - X_h}) \bullet 57.3 \end{bmatrix} \tag{15}
$$

$$
\boldsymbol{g}_2^{pirouette}(\boldsymbol{K}_d, \boldsymbol{x}_d) = \begin{bmatrix} H_{com} \\ \dot{H} \\ q \\ K_u u + K_{udot} \dot{u} + K_x (X_h - X_{hov}) + \theta_{trim} \\ p \\ -K_v v - K_{vdot} \dot{v} + K_y (Y_{hov} - Y_h) + \varphi_{trim} \\ r \\ \psi_{constant} \end{bmatrix} \tag{16}
$$

In Eq. (15), H_{com} is the constant altitude command which can be set according to ADS-33E-PRF, $\dot{H}$, p and q are the real time helicopter altitude changing rate, pitch and roll rate respectively. The reason is during the first step of the maneuver these states should keep 0 in ideal case, and this is the stability augmentation function which can be done by flight control system. Therefore, the pilot does not need to make compensation control for undesired responses of these 3 state variables. According to the first term of Eq. (5), the difference of these 3 rows will be 0 because $\boldsymbol{x}_d$ is the helicopter real time response vector too, and the result is no matter the values of these 3 states are, pilot compensation control for these states will always be 0. R_{com} and R are the required radius of pirouette and the helicopter real time radius around the circle respectively, θ_{trim} and φ_{trim} are pitch and roll angle at hover trim condition respectively. The heading of the helicopter is changing all the time during pirouette maneuver, so the yaw rate should not be zero, and that's why the yaw rate dose not set to be the helicopter real time value. The pilot should control the yaw rate based on current lateral translational speed and the distance to the circle center. Finally, the head of the helicopter should always point at the center of the circle, and the required yaw angle can be calculated based on the X, Y coordinates of the helicopter and the center point.

In Eq. (16), the helicopter enters hover condition, and the yaw rate should be 0 at this time. So the required yaw rate is set to be real time value for the same reason as above. The yaw angle is set to be constant such as the value when entering hover condition.

When the mathematical description function is determined, the next step is to calculation coefficient matrix in Eq. (5) at hover condition based on the preceding developed method. Finally, combing Eq. (1), Eq. (4) and Eq. (5), the pilot control time history of pirouette can be obtained.

Fig. 1 shows the pilot control solution for pirouette. At the beginning of this maneuver, the pilot moves the lateral stick to the right a bit to induce lateral speed, and at the same time steps the left pedal to make the helicopter turn left in order to keep the nose pointed at the center of circle. The longitudinal stick control is used to prevent pitching up due to lateral sideslip velocity. Since the roll angle and pitch angle is small during the whole maneuver, the collective stick compensation is not very obvious.

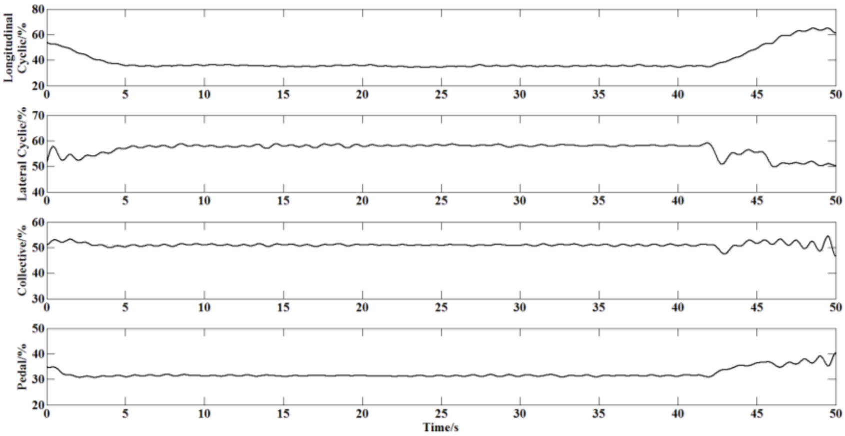
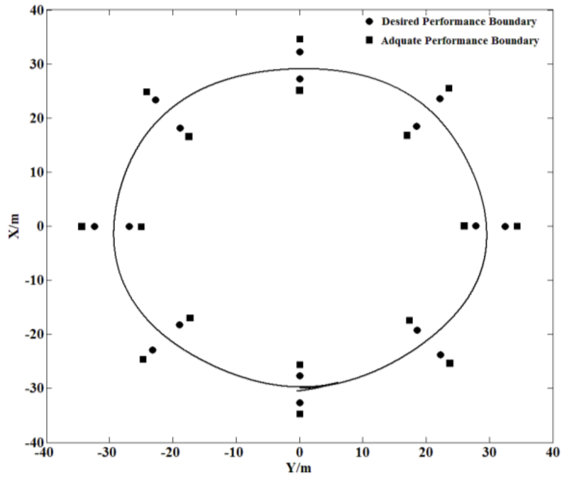


Fig. 1 The calculated pilot control time history of pirouette maneuver.

Taking the calculated pilot controls into Eq. (1), the flight states time history can be solved as shown in Fig. 2 ~ Fig. 4. It is obviously that the simulation results satisfy the entire performance standards in table 1.



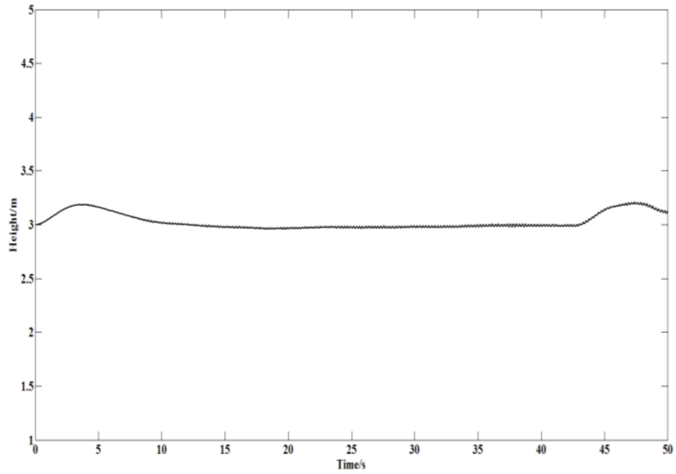


Fig.2. The simulated flight trajectory of pirouette maneuver. Fig.3 The altitude time history of pirouette maneuver.

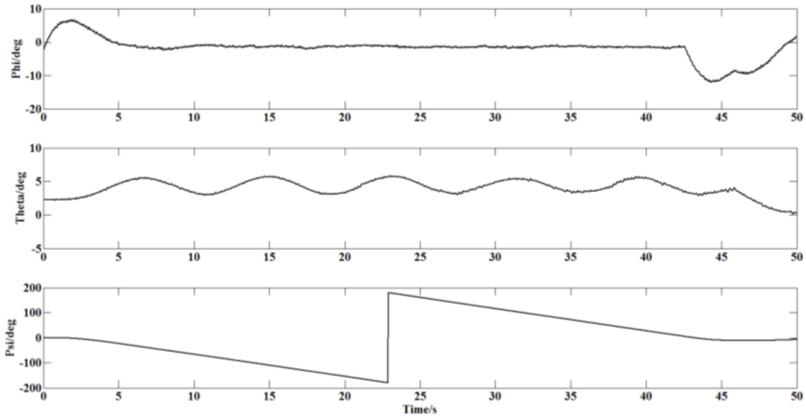


Fig.4 The Eula angle time history of pirouette maneuver.

The open loop solution for pilot control is also calculated as shown in Fig. 5 to check the differences between the closed loop and open loop inverse simulation. It can be found that in open loop situation where the flight control system is offline, the pilot will make compensation controls to eliminate all the undesired responses, the workload is increased considerably. On the other hand, this comparison shows the method developed for closed loop inverse simulation in this paper is effective.

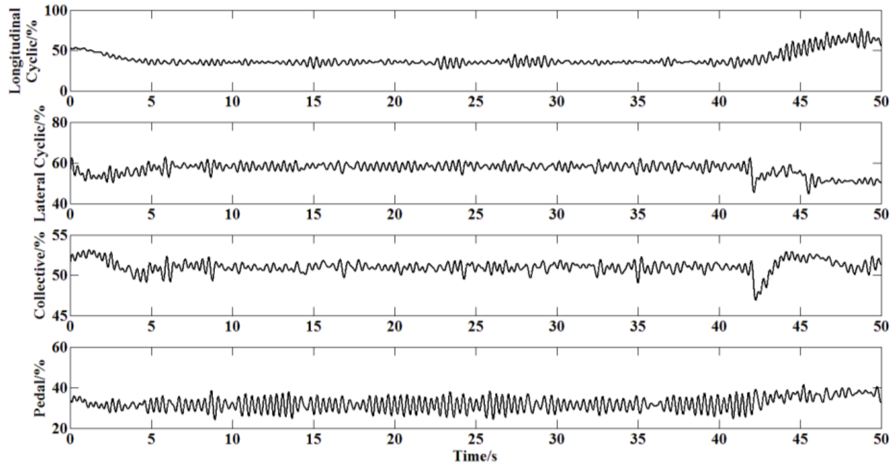


Fig.5 The calculated pilot control time history of pirouette maneuver with flight control system offline.

4.2. Vertical remask

The vertical remask is a vertical and lateral maneuver with aggressive agility requirement. The main performance standards for this maneuver are concluded in table 2.

Table 2 Performance standard of vertical remask maneuver.

Performance	Requirement (Desired)	Requirement (Adequate)
● Achieve an altitude of X or less within 6 seconds of initiating the maneuver	7.62 m	NA
● During initial hover, vertical descent and final stabilized hover, maintain longitudinal and lateral position within ±X m of reference point	2.4	3.6
● Maintain altitude after remask and during displacement within X m	±3	3 and -4.5
● Maintain lateral ground track within ±X m	3	4.5
● Maintain heading within ±X deg	10	15
● Achieving the final stabilized hover within X seconds of initiating the maneuver	15	25

The vertical remask maneuver can be divided into 2 steps, the first step is rapid vertical descent, and the second step is rapid lateral displacement. Therefore, there are also 2 different mathematical description functions for this maneuver, as shown in Eq. (17) and Eq. (18).

$$\boldsymbol{g}_1^{verticalremask}(\boldsymbol{K}_d, \boldsymbol{x}_d) = \begin{bmatrix} H_{com} \\ \dot{H}_{com} \\ q \\ K_u u + K_{udot}\dot{u} + K_x(X_h - X_{hov}) + \theta_{trim} \\ p \\ -K_v v - K_{vdot}\dot{v} + K_y(Y_{hov} - Y_h) + \varphi_{trim} \\ r \\ \psi_{constant} \end{bmatrix} \tag{17}$$

$$\boldsymbol{g}_2^{verticalremask}(\boldsymbol{K}_d, \boldsymbol{x}_d) = \begin{bmatrix} H_{com} \\ \dot{H} \\ q \\ K_u u + K_{udot}\dot{u} + K_x(X_h - X_{hov}) + \theta_{trim} \\ p \\ K_v(v_{com} - v) + \varphi_{trim} \\ r \\ \psi_{constant} \end{bmatrix} \tag{18}$$

In the first step, the helicopter performs rapid vertical descent to a prescribed altitude relative to a constant point. So in Eq. (17), the altitude is set to a constant value and the changing rate of altitude is also set to a constant value at first few seconds. When the altitude is close to the required one, the changing rate of altitude will set to be 0. Since the helicopter is required to hold longitudinal and lateral position in the vertical descent phase, the remaining description variables are calculated similar to hovering case in Eq. (16).

In the second step, the main flight course is lateral displacement, so the roll angle description variable is set according to sideslip speed requirement. The determination of other description variables is similar to the hovering case.

When the mathematical description of vertical remask maneuver is done, the same procedure as in pirouette maneuver simulation is performed to obtain the inverse simulation results. Fig. 6 shows the pilot control time history for implementing vertical remask, while Fig. 7 ~ Fig. 8 providing the simulated state responses time histories of this maneuver.

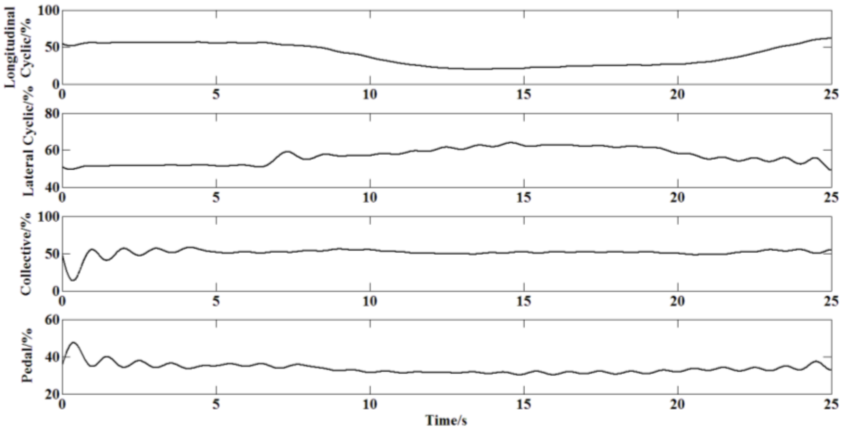


Fig.6 The calculated pilot control time history of vertical remask maneuver.

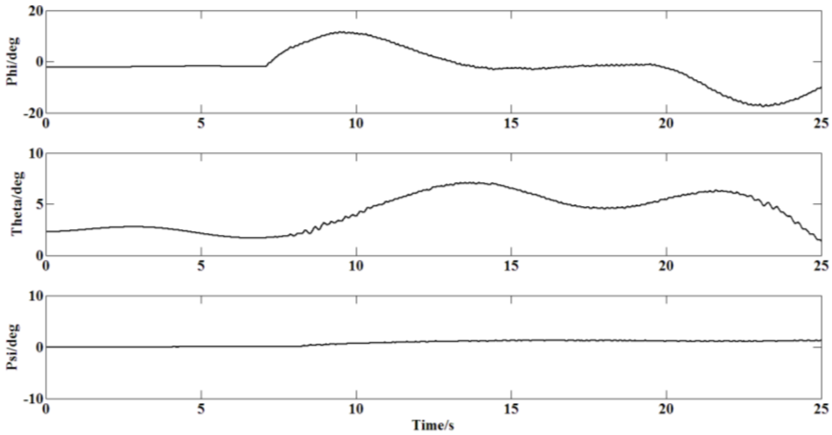


Fig.7 The Eula angle time history of vertical remask maneuver.

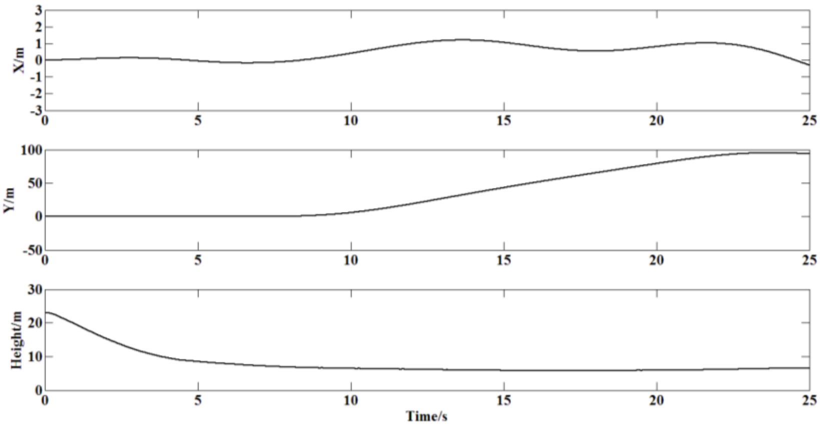


Fig.8 The flight trajectory time history of vertical remask maneuver.

At the beginning of this maneuver, the pilot decreases the collective to make the helicopter descend, while adjusting the pedal to keep the heading of the helicopter. Then at about 7 second, the pilot pulls the cyclic stick to the right to make the helicopter sideslip to the right rapidly. At the same time, the longitudinal stick control is used to prevent pitch up caused by longitudinal and lateral rotor flap coupling phenomenon.

It can be found in Fig. 7 and Fig. 8 that the UH-60 helicopter can perform the vertical remask maneuver with sufficient precision. However, it cannot finish this maneuver in 15 seconds, but it can be done within 25 seconds. Therefore, the UH-60 helicopter cannot reach the desired level of this maneuver, but it meets the adequate requirements. Since the UH-60 is a utility but not attack helicopter, the inverse simulation result is reasonable.

The inverse simulation of this maneuver with flight control system offline was also implemented as shown in Fig. 9. The same conclusion can be made as in pirouette maneuver.

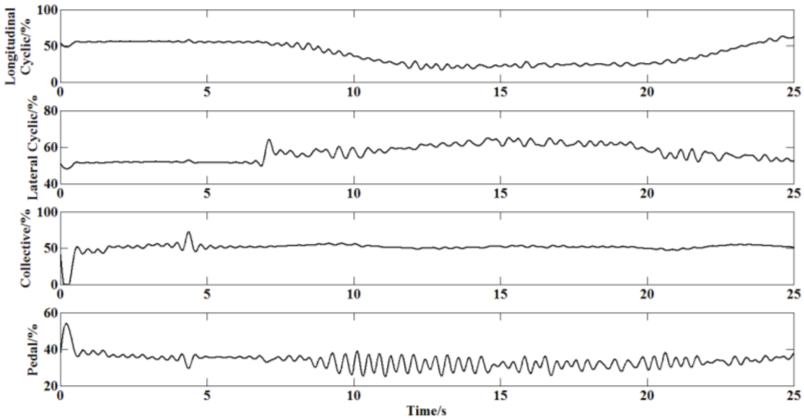


Fig.9 The calculated pilot control time history of vertical remask maneuver with flight control system offline.

4.3. High Yo-Yo

The high yo-yo is a target acquisition and tracking maneuver with aggressive agility requirement. This maneuver requires two aircraft to perform at the same time, and the test course is not static. So it is impossible to use conventional optimization based method to implement the inverse simulation of this maneuver. The performance standard for this maneuver in the ADS-33E-PRF is qualitative.

The high yo-yo maneuver can be divided into three steps. The first step is following, while the second step is deceleration by means of climbing, and the last step is pursuit. The relevant mathematical description function of these three steps can be found in Eq. (19) ~ Eq. (21).

(19)
$$\boldsymbol{g}_1^{highyoyo}(\boldsymbol{K}_d,\boldsymbol{x}_d)=\begin{bmatrix} H_{target} \\ \dot{H} \\ q \\ K_u(u-u_{com})+\theta_{trim} \\ p \\ -K_v v+K_y(Y_{target}-Y_h)+\varphi_{trim} \\ r \\ \psi_{constant} \end{bmatrix}$$

(20)
$$\boldsymbol{g}_2^{highyoyo}(\boldsymbol{K}_d,\boldsymbol{x}_d)=\begin{bmatrix} H+K_{hu}(u-u_{target}) \\ \dot{H} \\ q \\ K_u(u-u_{target})+\theta_{trim} \\ p \\ -K_v v+\varphi_{trim} \\ K_{r\psi}[\arctan(\frac{Y_{target}-Y_h}{X_{target}-X_h})\bullet 57.3-\psi] \\ \arctan(\frac{Y_{target}-Y_h}{X_{target}-X_h})\bullet 57.3 \end{bmatrix}$$

(21)
$$\boldsymbol{g}_3^{highyoyo}(\boldsymbol{K}_d,\boldsymbol{x}_d)=\begin{bmatrix} H_{target} \\ \dot{H} \\ q \\ K_u(u-u_{target})+K_{td}[TD_{com}-\sqrt{(X_h-X_{target})^2+(Y_h-Y_{target})^2}]+\theta_{trim} \\ p \\ -K_v v+\varphi_{trim} \\ K_{r\psi}[\arctan(\frac{Y_{target}-Y_h}{X_{target}-X_h})\bullet 57.3-\psi] \\ \arctan(\frac{Y_{target}-Y_h}{X_{target}-X_h})\bullet 57.3 \end{bmatrix}$$

In the first step, the test helicopter chases the target helicopter straightforward. So the altitude description variable is set to be the target helicopter's altitude, while the stabilization of changing rate of the altitude is left to the flight control system. The main control in this step is using cyclic stick to keep the test helicopter at a required forward flight speed, so the pitch angle description variable is set according to the speed command. In lateral channel, the roll angle description variable is set based on sideslip speed and lateral displacement to ensure the test helicopter behind the target helicopter all the time. The augmentation of angular rates is left to the flight control system.

In the second step, the test helicopter reduces the airspeed since the target helicopter does the same thing. On the other hand, the target helicopter makes a transient turn to try getting rid of the test helicopter. So the test helicopter should change its heading and keep pointing at the target helicopter. In order to implement these works, the pitch angle description variable is set according to the airspeed difference between the two helicopters. The altitude description variable is also set based on airspeed difference because the collective determines the rotor thrust which will influence the acceleration and deceleration of the helicopter. The yaw angle description variable is set according to the relative coordinate of the two aircraft, and the yaw rate is also set based on the current and required heading in order to make a rapid turn.

In the last step, the test helicopter will dive to the target helicopter and keep pursuing it. The mathematical description of this step is similar to the second step. The main differences are the altitude description variable is set to be the height of the target helicopter, and the pitch angle description variable is set based on both the airspeed difference of the aircraft as well as the required pursuit distance of the two helicopters.

When the mathematical description of high yo-yo is done, the same procedure can be performed to implement the inverse simulation of this maneuver. Fig. 10 gives the solution of pilot control time history, while Fig. 11 ~ Fig. 13 showing the simulated states time histories of this maneuver.

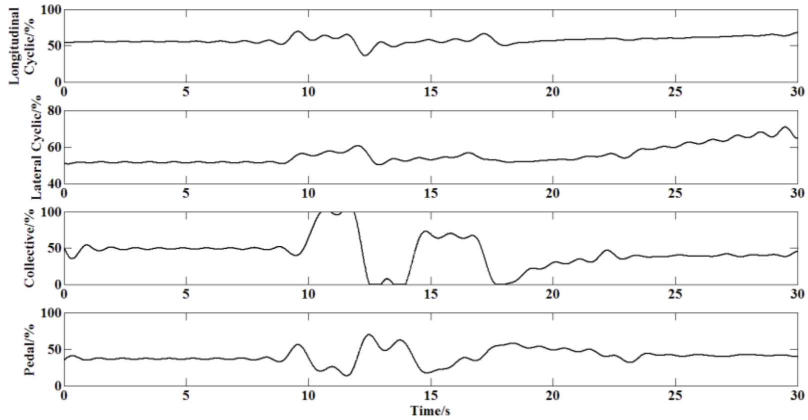


Fig.10 The calculated pilot control time history of high yo-yo maneuver.

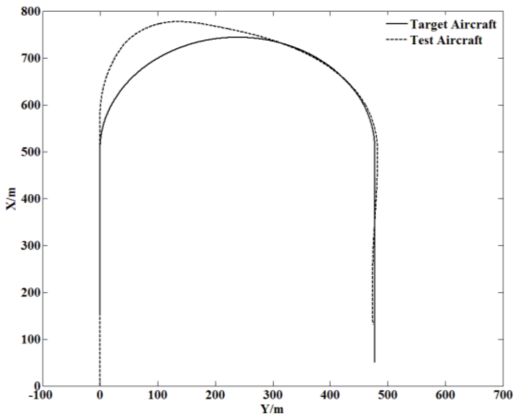


Fig.11 The simulated trajectory of high yo-yo maneuver.

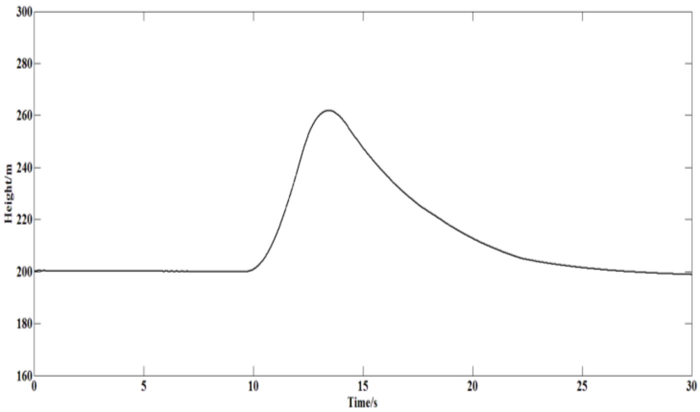


Fig.12 The simulated altitude time history of high yo-yo maneuver.

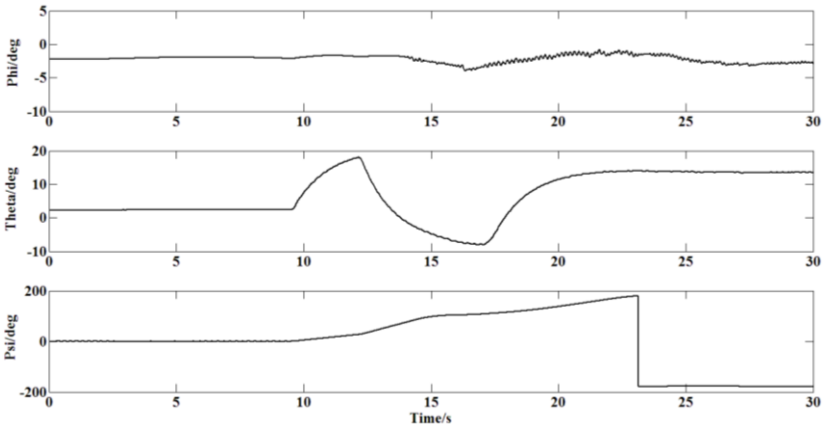


Fig.13 The Eula angle time history of high yo-yo maneuver.

In the first step, the test helicopter only need track the target helicopter at constant altitude and heading.

It is quite close to steady forward flight condition, and since the flight control system is online which can stabilize the helicopter in steady flight state, the pilot only need perform very small compensation control in this step. At about 8 second, the test helicopter begins pitch up to reduce its airspeed. The longitudinal cyclic stick is pulled back a bit then, and the collective is also increased to provide large rotor thrust which is helpful of reducing the airspeed. At the meantime, the pedal and lateral controls are applied to make the test helicopter turn toward to the target helicopter. After a rapid deceleration, the test helicopter begins to pursue the target helicopter, and the pilot applies all of the four controls to implement this.

The flight trajectory in Fig. 11 shows the good performance of the inverse simulation. The test helicopter has a delay in initiating turn right which is just required in the ADS-33E-PRF. The reason is to keep the test helicopter be-hind the target helicopter all the time for missile launch requirement.

Fig. 14 shows the inverse simulation result for high yo-yo maneuver with flight control system offline. It can be found that, the pilot workload for this maneuver is increased considerably without stability augmentation system, just the same phenomenon as the previous two maneuvers.

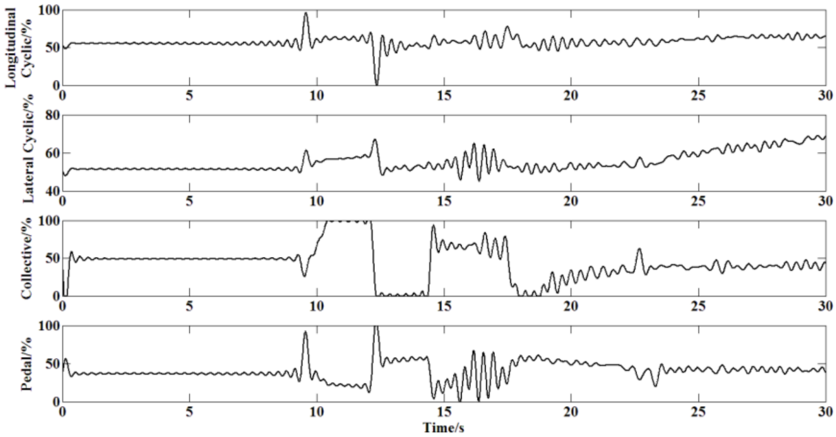


Fig.14 The calculated pilot control time history of high yo-yo maneuver with flight control system offline.

5. CONCLUSIONS

(1) A general method for closed loop inverse simulation of helicopter maneuver flight is developed which includes flight control system modeling, general mathematical description of maneuvers and pilot control calculation.

(2) The closed loop inverse simulation of three typical helicopter maneuvers defined in the ADS-33E_PRF with large differences in course pattern and agility requirements are implemented.

(3) The results show the method developed in this paper is capable of solving the inverse simulation problem for different kinds of maneuvers with high reliability as well as efficiency.

(4) The developed method can separate the pure pilot controls of each maneuver from flight control system out-put, and this improvement is very useful for engineering applications such as pilot training, simulation flight test etc.

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