Helicopter Flight Dynamics Modeling Using Simulink

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Abstract: In this paper, a mathematical model for conventional helicopter flight dynamics simulation based on the module of Simulink-Function is developed. The model does not need to call external programs or data, and can be directly compiled to form a dynamic link library, laying a foundation for the joint use of flight control systems of LABVIEW and other software. In the process of modeling, the main aerodynamic components of helicopter are considered comprehensively. Main rotor model is the key part of helicopter modeling, and the associated model of airfoil aerodynamics, inflow dynamics and blade flapping motion are all considered and discussed. Based on the modeling principle of modularity, the entire flight dynamics model is established in Simulink. The trim calculation and response analysis are carried out and compared with the helicopter flight data. The simulation results validate the rationality and accuracy of modeling methods. Finally, the simulation of an application of mission task is carried out to further verify the validity and usability of the model.

Key Words: Helicopter, Flight Dynamics, Simulink, Simulation

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1 INTRODUCTION

The numerical simulation model of helicopter flight dynamics has a very important position in the field of helicopter research. It is not only widely used in helicopter performance analysis and control system design and verification tasks, but also widely used in overall helicopter design, flight quality evaluation and pilot training. Compared with fix-wing airplane, the unique aerodynamic configuration of helicopters makes it much more complicated to model flight dynamics. The complete numerical simulation model of helicopter flight dynamics includes the multi-body dynamics of the helicopter, the degrees of freedom of the flap and swing of the rotor, and the aerodynamic interference effects. The fidelity of the simulation system is closely related to the perfection of the mathematical model. International helicopter numerical simulation researches have been carried out early, and many helicopter numerical models for engineering numerical simulation and ground real-time have been developed. Among them, ARMCOP [1], GENHEL [2] and FLIGHTLAB [3] are mature and well-known.

The existing flight dynamics model has strong integrity, but its flexibility and portability are usually poor. In order to be more suitable for early engineering design and analysis, a modular dynamics model that can interact directly with the flight control system is needed to better optimize each component. The challenge lies in that this is still a complete system, and it is necessary to deal with its interaction on the basis of modularization to ensure the accuracy of the model. Simulink is a block diagram design environment based on MATLAB, which can be used to model, simulate and analyze various dynamic systems, allowing users to simulate the operation of real dynamic systems in graphical mode with minimal cost. It has powerful interactive modeling and simulation functions, and its open structure allows users to expand the simulation environment and custom module libraries, while providing a fairly practical set of dedicated modules. Therefore, Simulink has received more and more attention and applications in the engineering community. In terms of the application of flight dynamics modeling, the S-function module and calling external calculation programs are used in the most of the existing researches [4-6], which cannot be directly compiled, which limits its further use on other flight control platforms.

In view of this, this paper establishes a UH-60 helicopter flight dynamics numerical model based on the Function module, which fully considers the dynamic characteristics of various aerodynamic components, the flap characteristics of the rotor, dynamic inflow and aerodynamic interference. The simulation model is finally implemented on the Simulink platform according to the modular idea, which ensures the flexibility and portability of the helicopter simulation system modeling. It can facilitate model extension and can be more conveniently applied to engineering analysis and design.

2 FLIGHT DYNAMICS MODEL

The numerical simulation model for UH-60 helicopter is established in this paper, which is a typical multi-body dynamics system. The flight dynamics model includes the aerodynamic model, kinematics model and the coupling and constrains of the rotor, tail rotor, fuselage, horizontal stabilizer and vertical fin. The aerodynamic force of the rotor on the fuselage, the interference effect of the rotor on the tail rotor, and the influence of the fuselage on the tail rotor are also explicitly considered in the simulation model established in this paper. Fig 1 shows the overall framework of the simulation model.

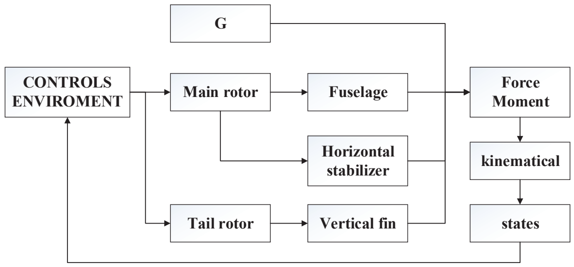


Fig 1. Helicopter flight dynamics model framework

This paper adopts a modular modeling idea, and regards the main aerodynamic links as independent simulation entities to generate their own forces and moments. The mutual interference between components directly affects the corresponding model. Some qualitative physical quantities are force, moment, attitude, and body axis velocity. This modular modeling idea ensures the flexibility of the simulation system, and is convenient to modify or replace and module without changing other modules.

The dynamics of rotor, body, tail rotor and inflow are independent and related to each other. The fuselage is connected to the rotor and the tail rotor through the resultant force and moment acting on the center of mass. The motion characteristics of the fuselage (velocity, acceleration and angle velocity) also affect the motion, force and moment characteristics of the rotor [7]. The helicopter aerodynamic model must separately establish the force and moment generated by each aerodynamic component, the body motion equation, the dynamic model of the induced velocity, and finally form a complete helicopter flight dynamics numerical model.

2.1 Main rotor aerodynamic model

The helicopter rotor aerodynamic model includes the establishment of airfoil aerodynamic model [2], induced velocity model and blade flap dynamics model. In the rotor model, it is assumed that the blade is rigid, the twist is linearly distributed, and only the flap freedom of the blade is considered. The flapping angle and the inflow angle are small angles. The linear quasi-steady aerodynamic model is used to calculate the blade profile aerodynamic force. The widely used Pitt-Peters first-order inflow model is introduced to establish the rotor induced velocity model, and the induced velocity is evenly distributed along the paddle without considering its dynamic response process.

The flapping motion of the blade is a first-order harmonic, and the motion form is shown in Fig 2. The rotation speed is Ω, the hinge offset is ε, the flapping hinge restraint is K_β. The moments acting on the flapping hinge include aerodynamic moment $M_{A\beta}$, moment of inertia $M_{I\beta}$ and restraining moment of the flapping spring $M_{K\beta}$.

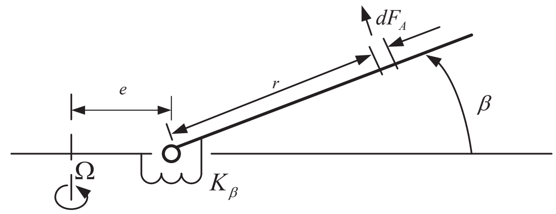


Fig 2. Blade flapping motion

For a rigid blade, the resultant moment at the flapping hinge of each blade will reach equilibrium during stable flight, and the flapping motion equation can be established in a single blade coordinate system.

$$M_{I\beta} + M_{K\beta} - M_{A\beta} = 0 \tag{1}$$

In flight mechanics analysis, it is more meaningful to study the overall flap state of the rotor than a single blade. This method has clear physical concepts and easy mathematical expression. Based on the multi-blade coordinate conversion method, the flapping motion equation in the rotating coordinate system can be converted to the non-rotating coordinate system [8]. The flapping equation of the blade can be expressed by a first-order Fourier series.

$$\beta_i = \beta_0 + \beta_{1c}\cos\psi_i + \beta_{1s}\sin\psi_i \tag{2}$$

where, β_0 is blade coning angle, β_{1c} is backward angle, β_{1s} is blade sideward angle.

Converting the single-blade coordinate form of the flapping motion to the multi-blade coordinate system, the following formula is obtained,

$$\begin{bmatrix} \ddot{a}_0 \\ \ddot{a}_1 \\ \ddot{b}_1 \end{bmatrix} + D\begin{bmatrix} \dot{a}_0 \\ \dot{a}_1 \\ \dot{b}_1 \end{bmatrix} + K\begin{bmatrix} a_0 \\ a_1 \\ b_1 \end{bmatrix} = f \tag{3}$$

where, D is damping matrix, K is stiffness matrix, f is excitation vector.

2.2 Aerodynamic model of other parts

(1) Tail rotor

The calculation method of tail rotor aerodynamic force is the same as that of main rotor, but the influence of its flapping motion is not considered, so as to achieve the accuracy of the model.

(2) Fuselage

The fuselage aerodynamic model is established according to the wind tunnel test data [9], and the functions of fuselage aerodynamic force and moment random body angle of attack and sideslip angle are obtained by curve fitting.

(3) Horizontal stabilizer and vertical fin

Horizontal stabilizer plays an important role in the longitudinal trim and pitch stability of helicopter, while vertical fin plays an important role in the course trim and stability of helicopter. Their aerodynamic forces and moments are calculated by lift line theory. For the horizontal stabilizer, the downwash effect of the main rotor and fuselage, and the incoming flow loss caused by the fuselage are considered. For the vertical fin, the influence of the tail rotor side wash flow is considered.

2.3 Flight dynamics equation

The resultant force and moment at the center of gravity of the aircraft can be obtained from the forces and moments of the rotor, tail rotor, fuselage, horizontal stabilizer and vertical fin acting on the body center of gravity respectively. According to Newton's second law, the dynamic equation of the aircraft is as follows.

$$\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix} = \begin{bmatrix} 0 & r & -q \\ -r & 0 & p \\ q & -p & 0 \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix} + \begin{bmatrix} -g\sin\theta \\ g\sin\phi\cos\theta \\ g\cos\phi\cos\phi \end{bmatrix} + \frac{1}{m} \begin{bmatrix} X_{sum} \\ Y_{sum} \\ Z_{sum} \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = I^{-1} \begin{bmatrix} 0 & r & -q \\ -r & 0 & p \\ q & -p & 0 \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} I \begin{bmatrix} p \\ q \\ r \end{bmatrix} + I^{-1} \begin{bmatrix} L_{sum} \\ M_{sum} \\ N_{sum} \end{bmatrix} \tag{5}$$

where, I is the matrix of the moment of inertia and the product of inertia, m is the mass of the aircraft, g is the acceleration of gravity. u, v, w is the velocity in each direction. p, q, r is the angular velocity in each direction.

The kinematic equation is as follows.

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi/\cos\theta & \cos\phi/\cos\theta \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{6}$$

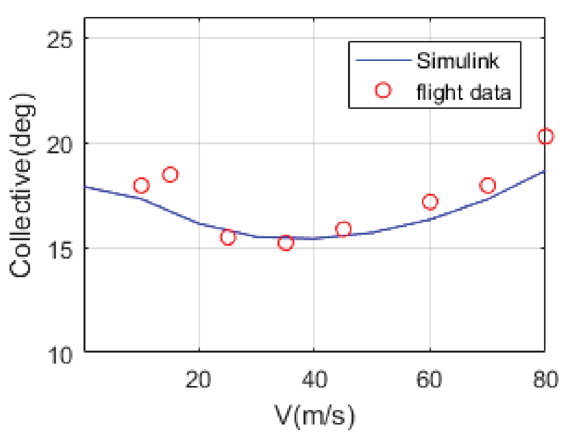
3 SIMULINK MODEL VERIFICATION

On the Simulink platform, according to the mathematical simulation model framework of helicopter flight dynamics and the derivation of aerodynamic model of each component, the whole simulation system is finally realized in modularization. The simulation system is divided into three parts: control variables (collective pitch, longitudinal cyclic pitch, lateral cyclic pitch and pedal), main aerodynamic components (main rotor, tail rotor, fuselage, horizontal stabilizer and vertical fin) and helicopter motion model. Among them, main rotor and tail rotor are modularized, including the induced velocity or flapping motion model.

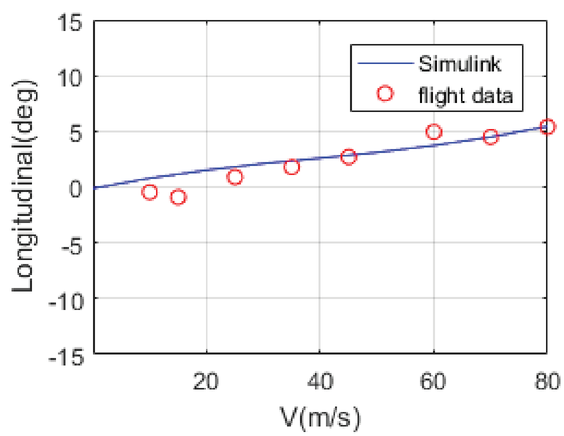
Aiming at the helicopter flight dynamics model on the Simulink platform, the UH-60 helicopter flight data in the literature [9] is used for comparison. According to the flight test conditions, the helicopter response to the pilot input under the condition of level flight is calculated. The rationality and accuracy of this model are verified by comparison with flight data.

3.1 Trim results validation

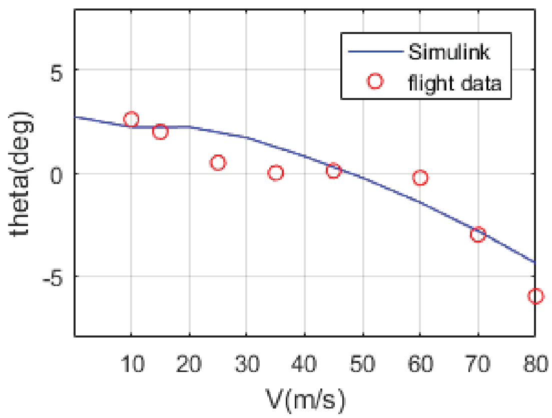
The comparison is shown in Fig 3. The solid line in the figure represents the trim curve of the model established in this article, and the circle represents the flight data. For the level flight conditions, the comparison is mainly performed on the longitudinal channels. It can be seen from figures that the maximum error of control is 1.67deg and the maximum error of attitude angle is 1.61deg between Simulink and Flight data. The variation trend of the two is basically the same. Considering the measurement accuracy and the instability of test environment, the flight dynamics model can be regarded as accurate. The trim calculation results also show a reasonable trend of change. The collective pitch has the characteristic bucket profile as a function of level flight speed. Longitudinal cyclic pitch increases with the increase of the level flight speed. With the increase of speed, the fuselage gradually transitions from the head-up attitude to the head-down attitude, while the yaw angle remains basically stable with a small amount of change.



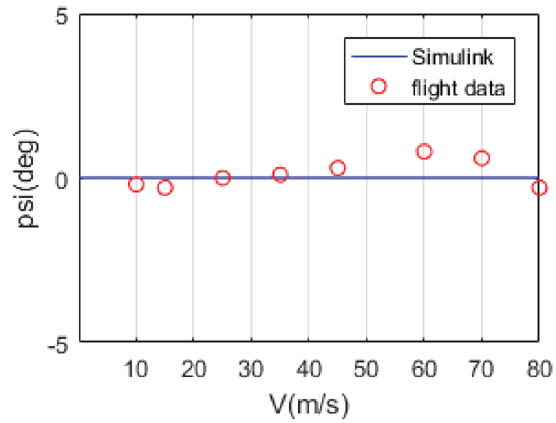
(a) Collective pitch



(b) Longitudinal cyclic pitch



(c) Pitch angle



(d) Yaw angle

Fig 3. Static trim of the helicopter in level flight

3.2 Control response analysis

The control response analysis is mainly to verify whether the response of helicopter body conforms to the laws of physics under the excitation of the control input, which is a key link to verify the accuracy of the flight mechanics model. Taking the trim value at 10*m/s* level flight as the initial value for dynamic response calculation, the body response under the condition of stable flight is analyzed. The response curve in Fig 4 shows the response history of the pitch angle and pitch angle velocity of the body when the forward step is applied to the longitudinal cyclic pitch. It can be seen from the figure that the longitudinal stick is pushed forward in the third second, and keeps the aircraft head down in accordance with the basic physical characteristics of the aircraft.

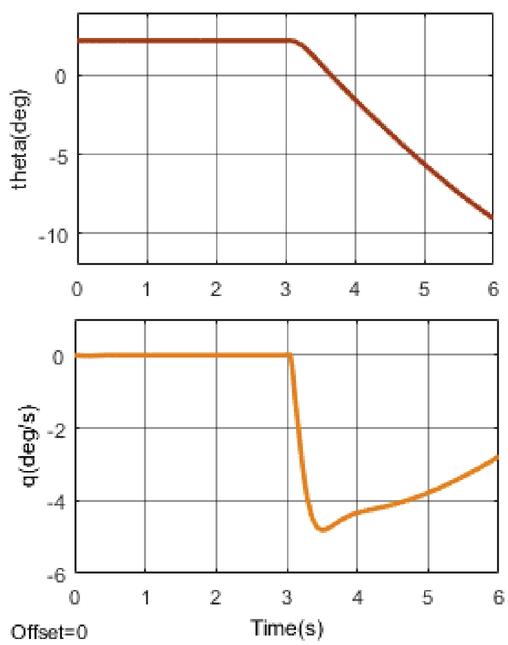


Fig 4. Pitch angle and pitch angle velocity step response curves

4 SIMULATION OF MISSION TASKS

Numerical simulation of mission task elements is an important application of flight dynamic models and one of the important foundations for helicopter flight quality evaluation. According to the simulation results, the evaluation of the performance level of helicopter mission tasks and the driving quality can be further carried out. Therefore, a simple state feedback is added on the basis of the above-mentioned dynamic model, and a simulation analysis is carried out for two typical task elements with different maneuvering levels. In the solution process, the driver dynamics model is integrated, that is, the driver perception process of the helicopter state response and the physiological process of applying the control input are considered.

4.1 Landing

The simulation results of the precision landing task are shown in Fig 5 and Fig 6. The landing starts after 0.5*s* in the hovering state and the landing is completed within 10s. It can be seen from Fig 5 that the longitudinal and lateral deviations during the landing of the helicopter are all within 0.1*m*, which meets the satisfactory performance indicators defined by the specification [10]. It can be seen from Fig 6 that the deviation of the yaw angle during the landing is less than 1°, which also reaches a satisfactory performance indicator. In summary, the model can achieve satisfactory performance indicators for landing task.

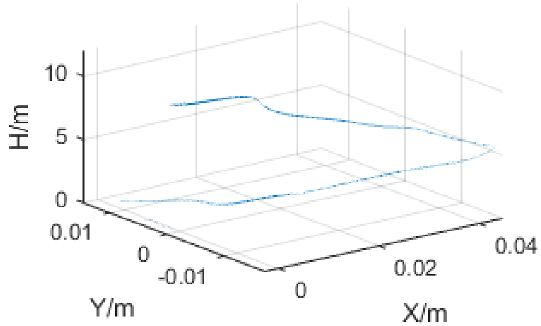


Fig 5. 3D trajectory of landing task simulation

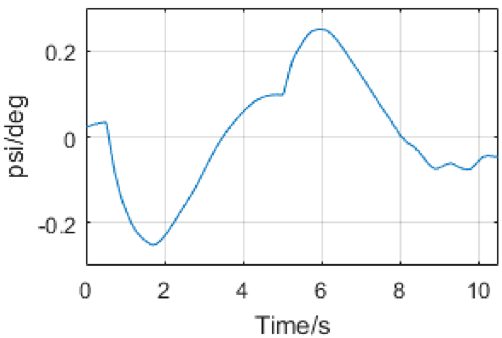


Fig 6. Yaw angle of landing task simulation

4.2 Slalom

The simulation solution results of the slalom task are shown in Fig 7 and Fig 8. It can be seen from figures that the flight trajectory meets the requirements of the specification. After the correction, the center line is used as the reference line to achieve level flight. The altitude changes and flight speed during the entire flight are also within the satisfactory performance range required by the specification. Throughout the simulation process of the task, the yaw angle basically changes synchronously with the flight trajectory, and the pitch and roll angles slightly change with the yaw maneuver during the flight process. In summary, the model can achieve satisfactory performance indicators for slalom task.

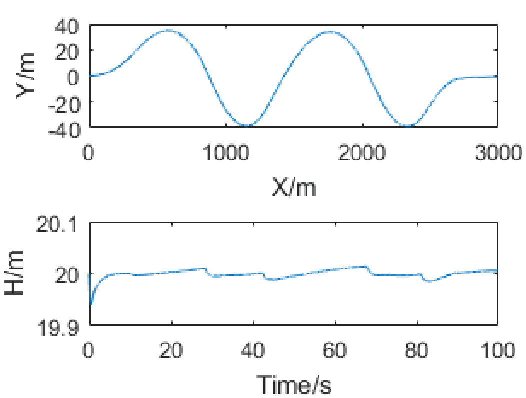


Fig 7. Flight trajectory of slalom task simulation

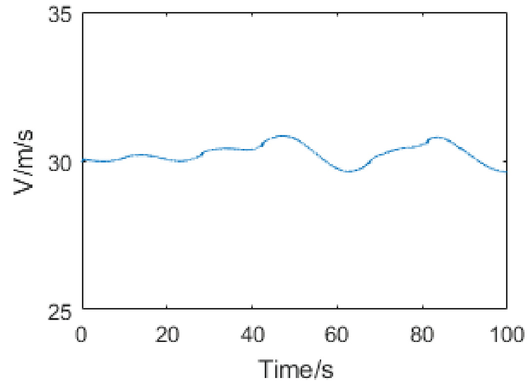


Fig 8. Flight speed of landing task simulation

5 CONCLUSIONS

The helicopter is a multi-body dynamic system with complex structure and aerodynamic characteristics. When the mathematical equations of the helicopter motion are established, it is necessary to comprehensively consider the physical models and mathematical expressions of each dynamic component, but also abstract and generalize according to the actual situation. The essential factors affecting the flight characteristics of the helicopter are captured and a high-precision numerical model is finally obtained.

In this paper, a universal, high-precision numerical simulation model of flight dynamics for a single-rotor helicopter with tail rotor is established. According to the modular modeling idea, the main aerodynamic components of the helicopter are respectively derived aerodynamic force and moment formulas, and the aerodynamic interference between them is fully considered to ensure the accuracy of the model.

The nonlinear numerical simulation model of the helicopter is finally realized on the Simulink platform. Compared with previous implementations based on C, Fortran and other programming languages, this implementation based entirely on block diagram structure has unparalleled superiority. It can more clearly reflect the hierarchy of model simulation models. It has better module encapsulation and is easy to be replaced or modified. It can also facilitate model extension, for example, the engine module is not considered in this paper, and can be easily integrated into the entire simulation model. In addition, if combined with MATLAB RTW toolbox or LABVIEW and other software, the model can be easily converted into executable code to achieve real-time simulation and other tasks.

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