A Simulation Model of a Helicopter Landing on a Ship

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***Abstract* — A modelling method is proposed focusing on the accuracy and efficiency of a collision model of a helicopter landing on a ship, a key and difficult aspect in helicopter simulators. Firstly, there kinds of axis systems are defined and the coordinate transformation model converts the landing gear coordinates into the ship body axis system thus the collision between the helicopter and the ship deck can be detected in a more simplified way. Meanwhile, the ship velocity transformation model converts the ship velocity into the helicopter body axis system thus the moving ship can be referred as static. Based on the support force model that simplifies the landing gears as spring-damper structures and the fraction force model, the force moment model is established. Finally, these models were implemented and integrated into the implementation of a six-degree-freedom helicopter model to verify the accuracy and efficiency of the models while the helicopter simulator lands on the ship deck simulated by a ship six-degree-freedom model. The experiment shows that the landing collision can be detected accurately and efficiently and the simulation forces generated by the collisions make the virtual helicopter motion characters fitting the real helicopter characters well. The method has been applied successfully in a helicopter simulator.**

Keywords - Helicopter; Landing on ship; Support force model; Fraction force model; Force moment model

I. INTRODUCTION

Ship-board helicopters which take off and land on ships fly over the oceans with roaring waves and complex meteorological conditions. There is a sharp difference between landing on a warship and landing on the ground[1,2,3]. The ship deck is small and always moves irregularly along with the wind and waves, and what is more, the ship buildings impact strong disturbances to the airflow around the ship deck. Therefore the landing of a helicopter on a ship is complicated and dangerous following this process[4,5]: The helicopter flies to the side-back of the ship deck aiming at the hover point and moves simultaneously with the ship. The pilot judges the swing cycle by observing the movement of the ship and flies the helicopter to the hover point quickly when it closes to the stable condition, which is followed by vertical landing. At this moment, the helicopter, which is acted by support forces and friction forces from the deck, impacts the ship deck and aligns with the ship eventually. The main technical difficulties for modelling this landing process[6,7,8] are comparing the relative positions of the helicopter landing gears and the ship deck and modelling the forces and force moments acting on landing gears when the helicopter impacts against the ship deck. This paper describes a method to establish a landing model that has been applied in a helicopter simulator consisting of a helicopter model with the landing model and a ship model as a landed platform, both being six-degree-freedom rigid bodies. When judging the impact of the helicopter against the ship deck, the method transforms the coordinate of landing gears from the helicopter body axis system to the ship body axis system and then judges whether the landing gears has been compressed and calculates the amount of the compression. When calculating the support forces generated by the impact of the ship deck, the method assimilates the landing gears to spring-damper structures. The support forces are relevant to the falling velocity of the helicopter relating to the ship and the amount of the compression of the landing gears. When calculating the helicopter velocity relating to the ship, the ship velocity is transformed to the helicopter body axis system to simplify the calculation of the forces and torques acting on the helicopter.

II. COORDINATE MODEL

A. Three Kinds of Axis Systems

- ECEF(Earth-Centered,Earth-Fixed): The ECEF[9] $Ox_c y_c z_c$ has its origin at the center of the Earth. y_c goes through the 0-degree meridian and z_c goes through the 90-degree meridian of east longitude both in the equatorial plane, and x_c is vertical to the equatorial plane and points to the North

Pole.

- Vehicle-carried normal earth axis system: A vehicle-carried normal earth axis system [9] is a helicopter-carried normal earth axis system or a ship-carried normal earth axis system. A helicopter-carried normal earth axis system $Ox_{hd}y_{hd}z_{hd}$ has its origin at the centroid of the helicopter. The plane $Ox_{hd}z_{hd}$ is the local horizontal plane with x_{hd} pointing to the north, z_{hd} pointing to the east and y_{hd} pointing up. The origin is represented by the longitude λ, the latitude ψ and the height h above the ground. A ship-carried normal earth axis system $Ox_{sd}y_{sd}z_{sd}$ is similar.
- Body axis system**:** A body axis system [9] is a helicopter body axis system or a ship body axis system. A helicopter body axis system $Ox_{ht}y_{ht}z_{ht}$ has its origin at the centroid of the aircraft. x_{ht} points to the front along with the longitudinal axis of the aircraft. y_{ht} is vertical to x_{ht} within the symmetry plane and points up, and z_{ht} is vertical to the symmetry plane and points to the right. A ship body axis system $Ox_{st}y_{st}z_{st}$ is similar.

B. *Landing Gear Coordinate Transformations*

In order to simplify detecting the landing collision, the coordinates of landing gears in the helicopter body axis system are transformed to ones in the ship body axis system, thus the ship movement can be ignored. These transformations showed below are done with each gear:

$$\begin{bmatrix} x_{hd} & y_{hd} & z_{hd} \end{bmatrix} = \begin{bmatrix} x_{ht} & y_{ht} & z_{ht} \end{bmatrix} A_x A_z A_y \quad (1)$$

$$\begin{bmatrix} x_c & y_c & z_c \end{bmatrix} = \begin{bmatrix} x_{hd} & y_{hd} + R + h_h & z_{hd} \end{bmatrix} B_z B_x \quad (2)$$

$$\begin{bmatrix} x_{sd} & y_{sd} & z_{sd} \end{bmatrix} = \begin{bmatrix} x_c & y_c & z_c \end{bmatrix} C_x C_z - \begin{bmatrix} 0 & R + h_s & 0 \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} x_{st} & y_{st} & z_{st} \end{bmatrix} = \begin{bmatrix} x_{sd} & y_{sd} & z_{sd} \end{bmatrix} D_y D_z D_x \quad (4)$$

Where

$$A_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\gamma_h & \sin\gamma_h \\ 0 & -\sin\gamma_h & \cos\gamma_h \end{bmatrix}, A_z = \begin{bmatrix} \cos\theta_h & \sin\theta_h & 0 \\ -\sin\theta_h & \cos\theta_h & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$A_y = \begin{bmatrix} \cos\psi_h & 0 & \sin\psi_h \\ 0 & 1 & 0 \\ -\sin\psi_h & 0 & \cos\psi_h \end{bmatrix}, B_z = \begin{bmatrix} \cos\phi_h & -\sin\phi_h & 0 \\ \sin\phi_h & \cos\phi_h & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$B_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\lambda_h & \sin\lambda_h \\ 0 & -\sin\lambda_h & \cos\lambda_h \end{bmatrix}, C_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\lambda_s & -\sin\lambda_s \\ 0 & \sin\lambda_s & \cos\lambda_s \end{bmatrix}$$

$$C_z = \begin{bmatrix} \cos\phi_s & \sin\phi_s & 0 \\ -\sin\phi_s & \cos\phi_s & 0 \\ 0 & 0 & 1 \end{bmatrix}, D_y = \begin{bmatrix} \cos\psi_s & 0 & -\sin\psi_s \\ 0 & 1 & 0 \\ \sin\psi_s & 0 & \cos\psi_s \end{bmatrix}$$

$$D_z = \begin{bmatrix} \cos\theta_s & -\sin\theta_s & 0 \\ \sin\theta_s & \cos\theta_s & 0 \\ 0 & 0 & 1 \end{bmatrix}, D_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\gamma_s & -\sin\gamma_s \\ 0 & \sin\gamma_s & \cos\gamma_s \end{bmatrix},$$

C. *Ship Velocity Transformation*

The ship velocity is transformed to the helicopter body axis system so as to calculate the relative speed between the helicopter and the ship and further to calculate the acting forces and the torques that the helicopter receives from the ship deck. Four calculating units of transformation matrix are involved, which are the ship body axis system to the ship-carried normal earth axis system, the ship-carried normal earth axis system to the ECEF, the ECEF to the helicopter-carried normal earth axis system, the helicopter-carried normal earth axis system to the helicopter body axis system. The transformation can be presented as follows:

$$\begin{bmatrix} vxs_{ht} & vys_{ht} & vzs_{ht} \end{bmatrix} = \begin{bmatrix} vx_{st} & vy_{st} & vz_{st} \end{bmatrix} D_x^{-1} D_z^{-1} D_y^{-1} C_z^{-1} C_x^{-1} B_x^{-1} B_z^{-1} A_y^{-1} A_z^{-1} A_x^{-1} \quad (5)$$

III. FORCE MODELS

The key to modelling the impact process while the helicopter landing is to develop the models of the forces and force moments acting on the helicopter generated by the ship deck [10,11,12,13,14,15]. The forces include the support forces along the oy-axis direction of the helicopter body, the longitudinal friction forces along the ox-axis and the sideways frication forces along the oz-axis.

A. *Support force model*

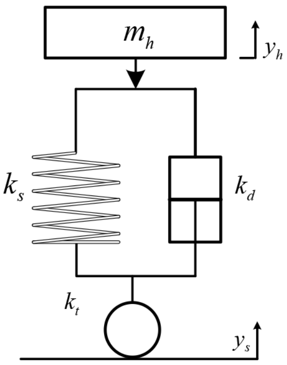

Fig.1 Refined Support Force Model

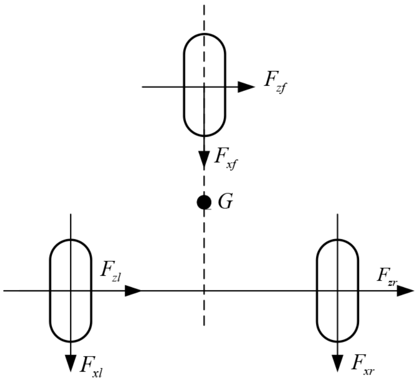

Fig.2 Friction Forces Suffered by Landing Gears

When the helicopter landing gears impact against the ship deck, the deck compresses the landing gears and generates support forces. The points of the support forces on the helicopter are the connection points of the landing gears with the body and the directions are upward along the $oy-anxis$ of the helicopter body axis system. The force conditions of each gear must be modelled due to each gear randomly impacting with the ship deck. On the condition of neglecting landing gear deformation and simplifying a landing gear as a spring-damper structure illustrated in Fig.(1), the impact between the helicopter and the ship can be described as a linear motion equation as follows:

$$m_h y_h^{''} + k_d (y_h^{'} - y_s^{'}) + k_s (y_h - y_s) + m_h g = 0 \quad (6)$$

where m_h is the mass of the helicopter; y_h and y_s are respectively the displacement of the helicopter and the ship deck. The support force is the function of compression stroke and the amount of compression speed. The compression stroke Δh can be calculated by the geometrical parameters such as the height of landing gears above the shipboard, initial length and so on. The gear coordinates (x_{st}, y_{st}, z_{st}) in the ship body axis system can be obtained by the landing gear coordinate transformations. $\Delta h = h_b - y_{st}$,where h_b is the distance from the ship deck to the ship centroid. The compression speed is calculated by the helicopter falling velocity and the deck movement velocity. The velocity component of the helicopter centroid v_{yt}, the components of angular velocity around the helicopter body axes $(\omega_x, \omega_y, \omega_z)$, the ship vertical movement velocity component on oy axis of the helicopter body axis system vys_{ht}, the landing velocity of the front gear, the left and right main gears are shown in Eq.(7):

$$\begin{aligned} v_1 &= v_{yt} + \omega_z \times x_{tf} - vys_{ht} \\ v_2 &= v_{yt} + \omega_z \times x_{tl} + \omega_x \times z_{tl} - vys_{ht} \\ v_3 &= v_{yt} + \omega_z \times x_{tr} + \omega_x \times z_{tr} - vys_{ht} \end{aligned} \quad (7)$$

In the equations, x_{tf} , x_{tl} , x_{tr} are respectively coordinates of the front, left and right landing gears in X-axis of the helicopter body axis system and z_{tl} , z_{tr} are respectively coordinates of the left and right landing gears in Z-axis.

B. Frication Force Model

There are two kinds of forces acting on the landing gears when a helicopter lands: one is the friction force F_x along the direction opposite the ox axis of the helicopter body axis system, which impedes the motion of the helicopter; the other is the friction force F_z perpendicular to the symmetry plane of the helicopter, which balances the lateral motion. As the helicopter is in the neutral lock state before landing and the direction of all gears does not deflect, it can be presumed that the friction forces F_x , F_z are parallel to ox axis and oz axis of the helicopter body axis system. The force analysis is shown in Fig.(2). The friction forces F_x , F_z are divided into static friction and dynamical friction, the division of which is based on the motion velocity of landing gears relative to the ship board. The gliding speed of the front, left and right landing gears can be calculated by the velocity components v_{xt} , v_{xt} of the helicopter centroid, the angle velocity components ω_x , ω_y , ω_z along the helicopter body axes, the horizontal ship velocity component vxs_{ht} on ox -axis of the helicopter body axis system, the horizontal ship velocity component

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vzs_{ht} on oz-axis of the helicopter body axis system.

The relative velocity along the ox-axis of the helicopter body axis system is:

$$\begin{aligned} v_{xf} &= v_{xt} - vys_{ht} \\ v_{xl} &= v_{xt} + \omega_y \times z_{tl} - vys_{ht} \\ v_{xr} &= v_{xt} + \omega_y \times x_{tl} - vys_{ht} \end{aligned} \tag{8}$$

The relative velocity along the oz-axis of the helicopter body axis system is:

$$\begin{aligned} v_{zf} &= v_{zt} - vys_{ht} \\ v_{zl} &= v_{zt} + \omega_x \times z_{tl} - vzs_{ht} \\ v_{zr} &= v_{xt} + \omega_x \times z_{tl} - vzs_{ht} \end{aligned} \tag{9}$$

The computational model of the friction force suffered by a landing gear along the ox-axis of the helicopter body axis system can be presented as follows and :

$$F_x = \begin{cases} k_f \times F_N & when|v_x| > v_{\lim} \\ k \times F_N & when|v_x| < v_{\lim} \end{cases} \tag{10}$$

where $v_{\lim}$ is the boundary velocity to judge a landing gear in motion or at rest. When the movement velocity of a landing gear is greater than the boundary velocity, the friction force suffered by the landing gear is dynamic friction, which is equal to the product of the support force F_N received by the landing gear and the dynamic friction factor k_f. The direction of the dynamic friction is opposite to the motion direction of the landing gear. When the movement velocity of a landing gear is less than the boundary velocity, the friction force suffered by the landing gear is static friction, which is equal to the product of static friction factor k and the support force F_N received by the landing gear. The friction model along oz-axis is similar.

C. *Force Moment Model*

Based on the computational models of support forces and friction forces established, the force moments [16,17] generated by these forces which act on landing gears can be obtained according to the coordinates of the landing gears in the helicopter body axis system and the distances from the landing gears to the ship board. The force moments can be described as follows:

$$\begin{aligned} M_{xt} &= F_{nf} \times z_{tl} + F_{nl} \times z_{tl} + F_{nr} \times z_{tr} - \\ &(F_{zf} + F_{zl} + F_{zr}) \times (y_{st} - h_b) \\ M_{yt} &= F_{nf} \times z_{tl} + F_{nl} \times z_{tl} + F_{nr} \times z_{tr} + \\ &F_{zf} \times x_{tf} + F_{zl} \times x_{tl} + F_{zr} \times x_{tr} \\ M_{zt} &= F_{nf} \times x_{tl} + F_{nl} \times x_{tl} + F_{nr} \times x_{tr} - \\ &(F_{xf} + F_{xl} + F_{xr}) \times (y_{st} - h_b) \end{aligned} \tag{11}$$

where h_b is the height from the ship deck to the ship centroid.

IV. SIMULATION VERIFICATION

Firstly, by means of C++ language, the support force model, the fraction model and the moment model were implemented and integrated into a six-degree-freedom flight equations of the helicopter. Secondly, a ship six-degree-freedom simulation model was developed as the landing platform and verified whether the helicopter can land on the ship platform smoothly and move in concert with the ship motion. In the experiment, the initial height of the ship deck was $h_b = 3.4m$ above the gravity center of the ship, the initial horizontal distance from the gravity center was $l_b = 53m$, the coordinate of the helicopter landing gears on Y-axis of the helicopter body axis system was $y_{ht} = -1.0$. Considering that the ship pitching, rolling and heaving have the greatest influence on the performance of landing, the experiment mainly focused on the three cases shown in Table 1.

Fig.(3) shows the parametric curves of the helicopter in case 1. It can be seen that the heights of the gravity center and the deck have no change when the ship rolling only. After the impact between the helicopter and the ship deck, the support forces are finally in balance with the gravity through a brief shock.

TABLE I. THE LANDING SIMULATION CONDITIONS

Case	Landing weight(kg)	Initial height(m)	Ship movement pattern
1	3200	8.5	$\omega_x = 0.314 \times \pi / 36.0 \times \sin(0.314t)$
2	3200	8.5	$\omega_z = 0.314 \times \pi / 72.0 \times \sin(0.314t)$
3	3200	8.5	$\omega_y = 0.314 \times \sin(0.314t)$

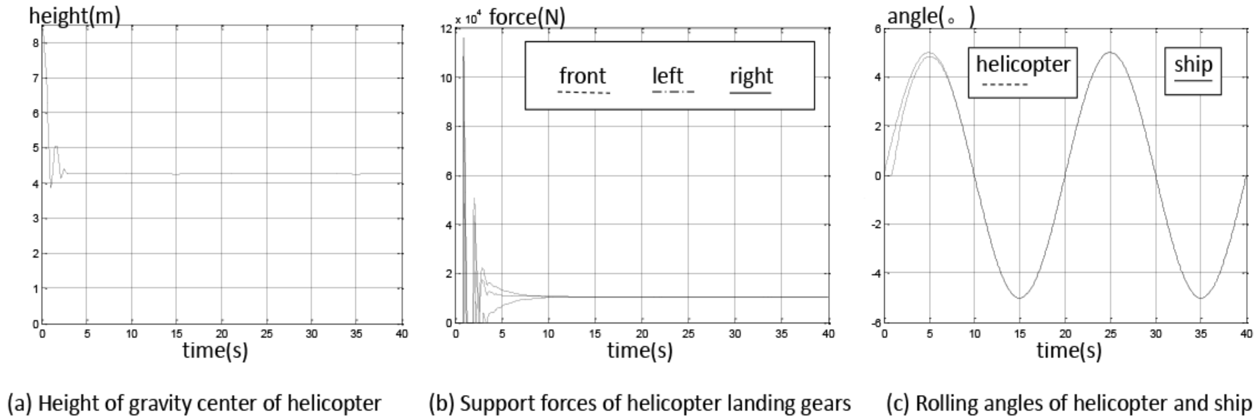


Fig.3 Simulation results in case 1

As last , the helicopter moves with the ship concertedly in sine rolling state and the height of the gravity center of the helicopter is stable at 4.3m.

Fig.(4) shows the parametric curves of the helicopter in case 2. Only when the ship is in pitching state, the center of gravity has no change but the deck height varies in sinusoidal direction. It can be seen that after the impact between the helicopter and the ship deck, the helicopter is finally in balance through a brief shock. As last, the helicopter moves with the ship concertedly in sine pitching state and the height of helicopter gravity center moves with the deck in sinusoidal direction.

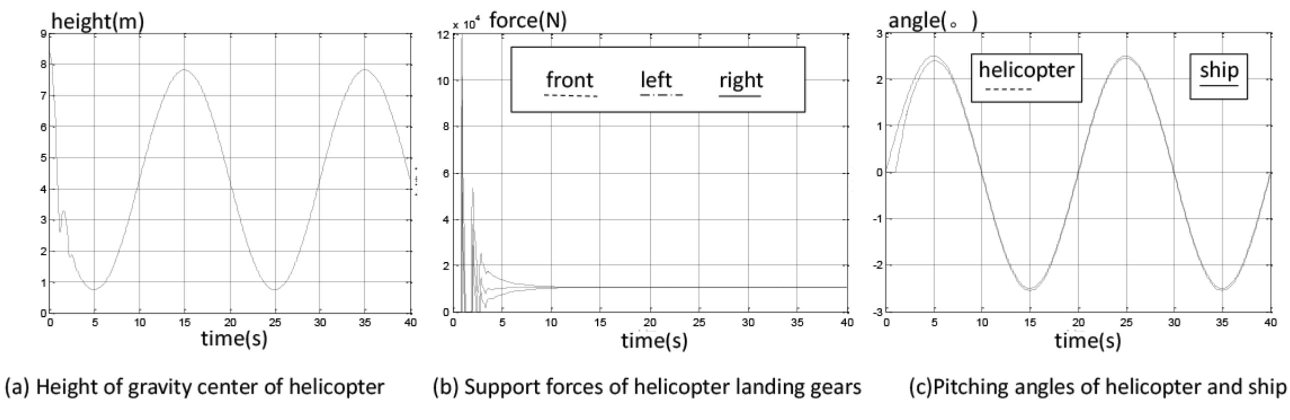
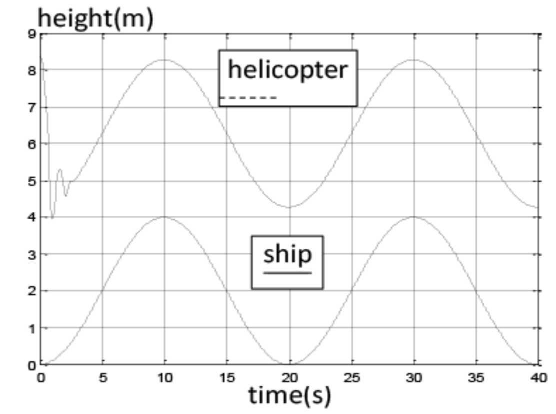
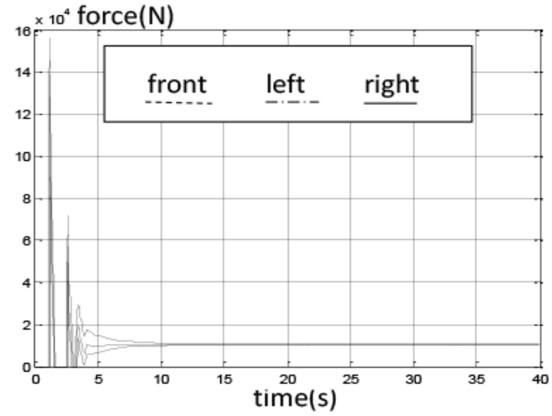


Fig.4 Simulation results in case 2

Fig.(5) shows the parametric curves of helicopter in case 3. It can be seen that heights of ship gravity center and the ship deck vary in sinusoidal direction only when the ship is in heaving state. After the impact between them, the helicopter is in balance through a brief shock. Ultimately, the helicopter moves with the ship concertedly in sine heaving state.



(a) Height of gravity centers of helicopter and ship



(b) Support forces of helicopter landing gears

Fig.5 Simulation results in case 3

V. CONCLUSION

The thesis proposed an impact modelling method which is suitable for ship-board helicopter flight simulators. In order to judge in a simple way whether the helicopter has landed, the method transforms the landing gear coordinates into the ship body axis system. For the convenience of calculating the forces and torques acting on the landing helicopter, the ship speed is transformed to the helicopter body axis system. When calculating support forces, the landing gear is refined as a simple spring-damper structure. The verification shows that the method can calculate the real-time forces acting on the wheels when the helicopter impacts against the ship deck and the helicopter can move coordinating with the ship. The method has been applied successfully in a helicopter simulator.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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