Research Article
Trajectory Track for the Landing of Carrier Aircraft with the Forecast on the Aircraft Carrier Deck Motion

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The paper presents a prediction method of deck lateral-directional motion for the control of landing trajectory of aircraft. Firstly, through the analysis of the process of aircraft returning to the ship, the modeling of the motion has been built. Secondly, in view of the delay of trajectory tracking captured in the actual process of aircraft landing on the ship, the error caused by the carrier motion signal has been analyzed. Based on the simulation results, the recommended prediction time of carrier motion has been proposed.

1. Introduction
Aircraft carrier is the most powerful weapon in the world. The length of aircraft carrier landing area is equivalent to one-tenth of airport on land. It is very difficult for the aircraft to land on the flight deck of carrier for some factors, such as deck movement and airflow interference.

When the fixed-wing carrier aircraft is landing on the flight deck of carrier with six-degree-of-freedom movement, the real-time tracking of deck motion is required to reduce the terminal error. During the track control process of the carrier aircraft tracking deck movement, there is an inevitable response delay, which causes the approach deviation. Aircraft carrier deck motion prediction is one of the most efficient ways to reduce the deviation and to improve the accuracy of landing. By providing the predicted deck motion information for the carrier aircraft, the error caused by the response delay can be compensated.

The realization of the aircraft carrier deck motion forecast is mainly based on the current deck movement and historical movement. The deck movement can be predicted in the next few seconds. A longer prediction time will result in a greater deviation of the prediction. While a too short prediction time is not enough to compensate for the response delay of the aircraft during the track control process.

This paper analyzed the relationship between the deck prediction time and the tracking accuracy by modeling F-18A landing motion and simulating the transverse heading motion, and the best timing of aircraft carrier deck transverse motion prediction is also studied.

2. Description of the Shipboard Landing Process
Usually, the fixed-wing carrier aircraft approach process is carried out following the “five-sided track-shaped” route, as shown in Figure 1, which is described as follows:

(1) Firstly the aircraft keeps the formation, puts down the arresting hook, and then flies over the end of the aircraft carrier or the starboard, at a constant flight speed and height.

(2) After the aircraft formation flies straightly along the aircraft carrier axis for a short time, the aircrafts disperse from the formation to the port side with a fixed interval.

(3) When the 180° turn is accomplished, the aircraft flies along the axe of aircraft carrier but against the direction of carrier motion. The pilot checks the weight of aircraft to confirm that it is less than the maximum weight.
(4) The carrier aircraft flies over the port side of the aircraft carrier and then makes another 180° turn and flies to the rear of the extension line of the centerline of bevel deck to intercept the glide path entrance, while keeping the flight speed and height during this process.

(5) When the carrier aircraft enters the glide path manually, the pilot controls the aircraft to land on the ship by using the isometric sliding technique, under the guidance of the optical assist system and the landing signal officer (LSO). During the landing, the path angle and the flight airspeed remain unchanged, and the engine is maintained at the military rated power state in case of increasing the thrust for go-around.

(6) The aircraft flies over the tail section of the aircraft carrier and continues to descend. The main landing gear tires to touch the deck, and the tail hook hangs one arresting gear cable. The aircraft slides an decelerated under the effect of arresting gear cable. If the tail hook misses all the arresting gear cables, the pilot must increase the throttle, go around, and then reland on the ship [1–5].

Figure 1 depicts the general process of landing for an aircraft by using a beveled deck, a constant angle of attack, and an optical assisted downslide. For different carrier aircrafts, the parameters of the glide path may not the same. Step (5) in the above process is the key process for the success of the aircraft landing. The process is shown in Figure 2.

In Figure 2, IM (in the middle) is the midpoint of the glide slope; IC (in close) is the point which is close to the glide slope. The carrier aircraft decides whether to continue to enter the ship or to go-around at this point. AR (at the ramp) is the end of the deck, and the height of the lowest point of the tail hook should be about 1 meter.

3. Modeling of Landing Process

The models for carrier-based aircraft landing include the aircraft carrier deck motion model, the carrier aircraft dynamics model, the aircraft carrier Landing Aid System model, and the carrier aircraft pilot control model (or the automatic controller model). The relationship between these models is shown in Figure 3. The motion information of the aircraft carrier and the aircraft are transmitted to the landing aid system model in order to output a deviation which requires compensation. The deviation is in the same time the input of the pilot control model or the automatic controller model. The movement of the aircraft carrier is tracked by eliminating the deviation caused by the movement of the aircraft carrier [6–10].
3.1. Aircraft Carrier Deck Motion Modeling. The 6-degree-of-freedom aircraft carrier deck motion model mainly includes the navigational motion and the 6-degree-of-freedom disturbance under the action of the ocean waves. It is generally considered that the 6-degree-of-freedom movement of the aircraft carrier deck satisfies the stationary stochastic process and can be described by stochastic process theory [11].

The literatures [11–13] give the motion spectrum curve of a certain aircraft carrier under certain sea conditions. Equations (1) to (4) give the transfer function of the aircraft carrier motion relative to white noise used in this paper.

\[
G_\phi = \frac{0.2384s^2}{s^4 + 0.2088s^3 + 0.3976s^2 + 0.3863s + 0.3423}, \tag{1}
\]

\[
G_\theta = \frac{0.334s^2}{s^4 + 0.604s^3 + 0.7966s^2 + 0.2063s + 0.1239}, \tag{2}
\]

\[
G_\psi = \frac{0.0058s^2 + 0.1520s + 1}{s^4 + 1.2s^3 + 1.98s^2 + 0.9720s + 0.6561}, \tag{3}
\]

\[
G_h = \frac{0.3536s^2 + 0.0141s}{s^4 + 0.38s^3 + 0.4977s^2 + 0.0836s + 0.0484}. \tag{4}
\]

3.2. Carrier Aircraft Dynamics Modeling. The main coordinate systems in this study include the inertial reference system, the bevel deck coordinate system, the aircraft body coordinate system, and the airflow coordinate system. All coordinate systems are right-handed.

Assuming that the Earth is stationary in the inertial space, ignoring the curvature of the Earth, and the F-18A carrier aircraft is a symmetrical rigid-body. With the above assumptions, the inertia products Ixy and Iyz are both considered as zero. In the body coordinate system, the complete motion equations of the carrier aircraft entering the ship are as shown in equations (5)–(7), where (5) is the centroid dynamic equation equations, (6) is the rotational dynamics equations, and (7) is the rotational kinematics equations [14].

![Figure 2: Shipboard aircraft entering glideslope](image1)

![Figure 3: Models for the aircraft carrier landing.](image2)
\[
\begin{align*}
V &= \frac{X}{m} - g \sin \theta \cos \alpha \cos \beta + \left(\frac{Y}{m} + g \sin \phi \cos \theta\right) \sin \beta \\
&\quad + \left(\frac{Z}{m} + g \cos \phi \cos \theta\right) \sin \alpha \cos \beta \\
\dot{\alpha} &= q + \frac{1}{\cos \beta} \left[ -\sin \alpha \left(\frac{X}{mV} - \frac{g}{V} \sin \theta + r \sin \beta\right) + \cos \alpha \left(\frac{Z}{mV} + \frac{g}{V} \cos \phi \cos \theta - p \sin \beta\right) \right] \\
\dot{\beta} &= p \sin \alpha - r \cos \alpha + \left(\frac{g}{V} \sin \theta - \frac{X}{mV}\right) \cos \alpha \sin \beta \\
&\quad + \left(\frac{g}{V} \cos \phi \cos \theta + \frac{Y}{mV}\right) \cos \beta - \left(\frac{g}{V} \cos \phi \cos \theta + \frac{Z}{mV}\right) \sin \alpha \sin \beta.
\end{align*}
\]

\[
\begin{align*}
L &= I_x \dot{\phi} - I_{xz}(\dot{r} + pq) + (I_z - I_y) \dot{qr}, \\
M &= I_y \dot{\phi} - I_{yz}(\dot{r}^2 - p^2) + (I_x - I_z) \dot{rp}, \\
N &= I_z \dot{\phi} - I_{zx}(\dot{p} - qr) + (I_y - I_x) \dot{pq}.
\end{align*}
\]

\[
\begin{align*}
\dot{\phi} &= p + q \sin \phi \tan \theta + r \cos \phi \tan \theta \\
\dot{\theta} &= q \cos \phi - r \sin \phi.
\end{align*}
\]

The abovementioned nonlinear motion equations of the carrier aircraft include eight equations, in which there are eight state variables, so the equations are closed. The state variables are \([V, \alpha, \beta, p, q, r, \phi, \theta]\) corresponding to velocity, angle of attack, side slip angle, roll angular velocity, pitch angular velocity, yaw angular velocity, roll angle, and pitch angle. \([X, Y, Z]\) represents the three-axis controllable force of the aircraft, and \([L, M, N]\) represents the three-axis controllable torque of the aircraft. The controllable force of the aircraft can be calculated by the formula (8), and \([L, D, C]\) represents the three-axis aerodynamic force of the aircraft, i.e., lift, drag, and side force.

\[
\begin{align*}
X &= -D \cos \alpha \cos \beta - C \cos \alpha \sin \beta + L \sin \alpha + T \cos \phi, \\
Y &= -D \sin \beta + C \cos \beta, \\
Z &= -D \sin \alpha \cos \beta - C \sin \alpha \sin \beta - L \cos \alpha - T \sin \phi.
\end{align*}
\]

Since \(a\) and \(\beta\) are small enough during the aircraft-entering process, it is reasonable to take the approximation that \(\sin a = a, \cos a \approx 1, \sin \beta \approx \beta,\) and \(\cos \beta \approx 1.\) Moreover, in the actual calculation, as \(|\beta|_{\text{max}} < 0.5°\), formula (8) can be further simplified to the centroid dynamics equation, as follows:

\[
\begin{align*}
\dot{V} &= \frac{X}{m} - g \sin \theta, \\
\dot{\alpha} &= q + \frac{Z}{mV} + \frac{g}{V} \cos \phi \cos \theta - p\beta, \\
\dot{\beta} &= p\alpha - r + \frac{g}{V} \sin \phi \cos \theta + \frac{Y}{mV}.
\end{align*}
\]

Thus, the controllable force equations are

\[
\begin{align*}
X &= -D + La + T, \\
Y &= C, \\
Z &= -Da - L.
\end{align*}
\]

### 3.3. Design of the Landing Aid System on the Carrier

The role of the aircraft carrier landing aid system is to combine the data of the aircraft carrier motion and the flight state of the aircraft in order to obtain the command deviation that needs to be compensated for the safe landing. Then, the command signal is inputted to the automatic ship controller or pilot for further operations of aircraft and for compensating the deviations [15–20].

### 3.4. Design of Pilot Control Model for Carrier Aircraft

Manual control model during the aircraft entering the ship is designed in this section. The role of the pilot control is to give the required command roll angle based on the command deviation and manipulate the aircraft for the corresponding maneuver. The difference is that the manually control is limited by the psychological and physiological conditions of the pilot, and the structural form and parameter values have certain limits. The deviation compensation circuit under pilot control is shown in Figure 4.

The classic pilot model contains three parts: time delay, gain and phase compensation, and neuromuscular lag. Experiments show that the minimum response time of humans to external stimuli increases with the stimulation frequency, and the delay phase increases linearly. Therefore, the delay link can be used to characterize the pilot’s characteristics. In other words, the pilot’s reaction time delay can be described by the delay link. Limited by physiological conditions, the delay time for the brain to respond to visual input information is approximately 0.15 seconds. Gain and phase compensation is described by pilot gain and lead-lag
networks. The neuromuscular system is equivalent to the actuator of the control system. When the muscle receives the motion command from the brain, the muscle fiber contracts asynchronously, presenting exponential response characteristics of time domain due to inertia. The inertial link can be used to approximate the pilot’s neuromuscular hysteresis characteristics. The time constant of inertial link is usually taken as 0.1 to 0.2 seconds.

Delay in response time and neuromuscular lag are inherent characteristics of human beings and are uncontrollable. The classic McRuer pilot model combines these two features into a delay link when they are used for flight quality evaluation, with an equivalent time parameter of 0.3 seconds. Therefore, the basic form of the McRuer model can be expressed as

$$Y_p(s) = K_e e^{-\tau_d T_L s} \frac{1}{T_L s + 1}$$

(11)

where $\tau_d$ represents the pilot’s maneuver delay, $K_e$ is the pilot’s gain, and $T_L$ and $T_I$ are the pilot’s lead and lag compensation time constant. When the inner loop is closed, the corner frequency of the outer loop is about 1/4 of the inner loop.

Bode diagram shown in Figure 5 is used for parameter adjustment. Considering the human’s physiological and psychological constraints, the values of parameters in the final pilot model are $K_e = 0.008; \tau_d = 0.1 \text{s}; T_L = 6 \text{s};$ and $T_I = 0.65 \text{s}.$

Guide tracking is performed using a 0.1 Hz command compensation signal, and the tracking curve is shown in Figure 6.

It can be inferred from Figure 6 that, within the allowable range of the aircraft’s operation, the response offset cannot fully track the upper command offset, and there will be a time delay of about 2 s $\sim$ 3 s. The curves of the roll angle and the aileron declination angle are shown in Figures 7 and 8.

3.5. Design of Carrier Aircraft Automatic Controller Model. During the approaching of the carrier aircraft, the 6-degree-of-freedom disturbance of the aircraft carrier, especially the yawing motion, will shift the glide slope. In order to make the carrier aircraft enter the ship safely and reduce the deviation, it is necessary to ensure that the downward trajectory of aircraft is centered with the beveled deck centerline: the aircraft needs to land on the ship along the glide slope. Therefore, it is necessary to compensate the deviation caused by the movement of the aircraft carrier.

Figure 9 shows the compensation of deviation of the transverse direction to the aircraft carrier. Due to the 6-degree-of-freedom disturbance of the aircraft carrier, the centerline of the beveled deck has a certain angular offset. The carrier aircraft needs to operate accordingly, so that the landing trajectory is centered with the centerline of the beveled deck, and the corresponding compensation $Y_{cmd}$ is

$$Y_{cmd} = |OC| \times \tan(\psi),$$

(12)

where OC is the distance from the carrier aircraft to the target deck of the aircraft carrier deck and $\psi$ is the
The parameter in equation (13) can be adjusted by using the Bode diagram shown in Figure 11 so that the condition that the corner frequency of the outer loop is less than 1/4 of the inner loop can be met. With the above process, the resulting parameter values are $k_k = 0.015$; $a_k = 8$; and $T_k = 0.3$ s.

The guide tracking is still performed with a 0.1 Hz command compensation signal. The tracking curve is shown in Figure 12.

The change of the lateral side track of the carrier aircraft is obtained after the roll angle is integrated twice, so there is a delay in time, which belongs to a slow change process. It can be learned from Figure 12 that although the automata is designed with advanced compensation characteristics, the displacement deviation cannot fully track the upper command offset within the allowable range of the aircraft’s operation with the existence of a certain time delay. The curves of the aileron deflection angle and roll angle are shown, respectively, in Figures 13 and 14.

### 4. Simulation on the Carrier Aircraft

#### Transverse Motion

Firstly, the actual motion data generated by the aircraft carrier deck motion simulator is used to simulate the transverse motion of the carrier aircraft, including the manual control landing process and the automatic control landing process.

Then, the aircraft carrier deck motion prediction data is used to carry out the simulation of the aircraft transverse
direction motion, and the manual control landing process and the automatic control landing process are both included.

4.1. Simulation of Transverse Motion of Carrier Aircraft Based on Actual Aircraft Carrier Deck Movement Data. The initial conditions of the simulation are as follows: the approach speed is 70 m/s, the glide slope angle is $-3.5^\circ$, the initial pitch angle is $2.71^\circ$, the initial angle of attack is $6.21^\circ$, the initial roll angle and yaw angle are both $0^\circ$, and and the initial height deviation is 0 m. The center deviation is 0 m, and the horizontal deviation is 0 m.

4.1.1. Simulation of Automatic Control Approach. Under the above initial conditions, the process of aircraft approach under the control of the automata is simulated. The calculation results are shown, respectively, in Figures 15–19.

It can be seen from the above results that the movement of the aircraft carrier, especially the yawing motion, will cause the offset of the ideal glide slope of the ship. The latter which will require the aircraft to perform the corresponding maneuver to track the ideal glide slope during the landing
process. The curve of the yaw angle during the entire approach is shown in Figure 15. The compensation curve for the command is shown in Figure 16. The yawing angle is basically changed between $[-1, 1]$ degree. With the variation of the yawing angle, the deviation that needs to be compensated also changes. Besides, the reduction of distance from the aircraft carrier deck leads to the decrease of the deviation that needs to be compensated.

Due to the limitation of aircraft maneuverability, the trajectory tracking characteristics of the carrier aircraft have a time delay of 2s to 3s, which ultimately results in an approach deviation of $-1.25$ m.

To sum up the results shown in Figures 17 and 18, the roll angle of the carrier aircraft has good tracking characteristics under the condition of automatic control of the aircraft approach. However, due to the limitation of the maneuverability of the aircraft, its trajectory tracking characteristics are not good, and an inevitable time delay of approximately 2 to 3 s is existed. The final resulting approach deviation is $-1.57$ m.

4.1.2. Simulation Results with the Manual Control Approach. In this section, the aircraft approach process under manual control is simulated with the same conditions in Section 4.1.1. The results are shown from Figures 20–24. It can be seen that the roll angle has good tracking characteristics, but the tracking of the deviation still has a certain time delay, which is about 2 to 3 s, eventually leading to a deviation of $-1.25$ m.

Besides, according to the deflection angle curve of the aileron in Figure 24, the aileron deflection angle frequency is high during this process, which indicates that the pilot’s operating load is high.

4.2. Simulation of Carrier Aircraft Transverse Motion Based on the Predicted Aircraft Carrier Motion Data. Firstly, the prediction technology of the aircraft carrier motion is used to predict the motion data for a period of time based on the measured aircraft carrier motion data. Then, the predicted
Figure 19: Aileron deflection angle curve.

Figure 20: Yaw angle curve.

Figure 21: Deviation curve.

Figure 22: Roll angle curve.

Figure 23: Offset curve.

Figure 24: Aileron deflection angle curve.
motion data is inputted to the aircraft carrier assist system, and the effectiveness of data prediction technology in aircraft approach is verified by simulation.

4.2.1. Simulation with Automatic Control Aircraft Approach Based on Aircraft Motion Prediction. From the simulation results in Section 4.1, the tracking compensation of the aircraft approach trajectory has a time delay of about 2~3 s. In this section, the carrier motion data 2 s after prediction is added to the automatic approach system. The results are shown in Figures 25 and 26. The final approach deviation is 0.23 m.

4.2.2. Simulation with Manual Control Approach Based on Prediction. The predicted aircraft carrier motion data of 2 s is added to the manual control approach system. The simulation results are shown in Figures 27 and 28. The final approach deviation is −0.77 m.

With the analysis of the results from Figures 25 to 28, it can be demonstrated that when the aircraft carrier motion data is predicted, the motion offset of the carrier aircraft can basically keep up with the command offset.

5. Conclusion

In this paper, the prediction method of aircraft carrier motion data is studied, and the main conclusions are as follows:

(1) The simulation results of the aircraft landing show that the rolling angle of the aircraft is trackable, but the trajectory tracking deviation has a time delay of about 2~3 s due to the limitation of the maneuverability of the aircraft itself.

(2) During the aircraft landing, the carrier’s yaw angle will cause the tracking deviation of aircraft trajectory, so that the pilot must make corresponding
manipulation of compensation to achieve the purpose of safe landing. During this process, the pilot’s handling load is high.

(3) Via the prediction of carrier motion data, the subsequent aircraft carrier motion data can be obtained. The prediction result during 1~3 s can basically meet the requirements. The simulation is carried out by adding the aircraft carrier motion data of 2 s with prediction to the aircraft landing system, and the results show that the trajectory tracking effect of the carrier aircraft is satisfying since the ship’s deviation decreases.

Data Availability
No data were used to support this study.

Conflicts of Interest
The authors declare that they have no conflicts of interest.

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