To cite this article: YANG L, XU D H. Aircraft carrier landing process simulation based on extremely short-term prediction of ship motion[J/OL]. Chinese Journal of Ship Research, 2018, 13(4). http://www.ship-research.com/EN/Y2018/V13/I4/99.

DOI: 10.19693/j.issn.1673-3185.01193

Aircraft carrier landing process simulation based on extremely short-term prediction of ship motion

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Abstract: [**Objectives**] Aircraft carrier landing is the key part of the whole flight process of carrier-based aircraft, and the technology design is difficult due to ship motion. [**Methods**] Based on the extremely short-term prediction method, this paper develops an aircraft landing simulation. First, based on the traditional extremely short-term prediction of ship motion, a method is proposed for determining the best prediction method by matching the waveform of the predicted signal combined with affine transformation. Next, an aircraft carrier landing guidance system is built on the basis of light beam guidance, and three landing end point errors for measuring the landing guidance system are presented. Finally, the aircraft carrier landing process is simulated, the errors between ideal approach path and tracking error of landing aircraft analyzed, and landing end point errors obtained. [**Results**] It can be seen from the simulation results that the landing points of aircraft are relatively concentrated, with most located within the scope of ideal landing points. The end point errors satisfy the requirements of landing guidance system standards. [**Conclusions**] The simulation results in this paper offer great reference value for the study of aircraft carrier landing.

Key words: carrier-based aircraft; landing guidance; extremely short-term motion prediction; landing point distribution; end point errors

CLC number: U666.1

0 Introduction

Aircraft carrier landing technology is an important guarantee for the combat capability of aircraft carrier battle groups, and is also a research focus on flight mechanics and control[1-2]. At present, only a few countries with aircraft carriers have mastered the core of this technology, such as the United States, Britain, France and Russia.

Compared with the land-based landing, aircraft carrier landing is technically very difficult, due to the hull motion and the special airflow field around the flight deck[3-5]. The pilot must accurately control the track and keep the carrier-based aircraft engage with the hull at the predetermined landing points with appropriate speed, attitude and relative position so as to safely complete arresting landing[6-7]. At present, the most widely used landing technology is the equiangular glide technology. In the final stage of the landing, the carrier-based aircraft maintains the same glide track angle, pitch angle, speed and sinking rate after intercepting the appropriate glide track until it engages with the flight deck to achieve the impact landing[8-9]. The advantage of this technology is that within the most critical 20 s before the ship is engaged, the pilot only needs to keep the existing flight state and correct the error caused by the ship motion and airflow field, thus avoiding possible errors and dangers brought by complicated operations[10-11]. The key to the equiangular glide technology is that the pilot must accurately obtain the glide track and its relative position information. The

Received: 2018-02-08

Supported by: General Project of State Key Laboratory of Robotics and System (SKLRS-2018-KF-120)

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optical landing system based on the Fresnel optical field is the main used method at present, which can provide a light beam-based gliding slope for the carrier-based aircraft in the air, thereby guiding the carrier-based aircraft to land along the reference light beam track[12-13]. In addition, the ship motion not only affects the relative position of the carrier-based aircraft, but also affects the guidance of the optical landing system and the airflow field around the hull. It is an important decision-making basis for the selection of the takeoff and landing timing of carrier-based aircraft. In reality, several different prediction algorithms are usually used to predict the motion attitude of ship, and the optimal prediction algorithm is determined by comparing the mean square error between the predicted and actual values[14]. The practical application shows that when there is a phase difference between the predicted value and the actual value, the error between the two is amplified so that the true optimal algorithm may be excluded. For this reason, this paper will adopt an accuracy analysis method based on waveform matching and affine transformation to eliminate the influence of the extremely short-term motion phase difference obtained by different prediction algorithms, so as to determine the optimal algorithm and predict the motion attitude of the ship in a short period of time. This paper will take the US carrier-based aircraft as the research subject, consider the influence of ship motion on the carrier-based aircraft, and combine the guiding technology of the reference light beam to design a carrier aircraft landing control system so as to analyze the landing end point errors and predict the landing points distribution, which can provide a reference for the determination of the aircraft carrier landing method and the reasonable layout of the arresting cable.

1 Extremely short-term motion prediction technology for carrier-based aircraft

Due to the wave effect, the sailing ship will generate motion with six degrees of freedom, which directly affects the safe landing of the carrier-based aircraft. According to the time history of the moving ships, the time-history data can be processed by Kalman filter, time series analysis and spectrum estimation method to predict the motion posture of ships in a short time in the future, which is called the extremely short-term motion prediction of ships. The extremely short-term motion prediction value is an important basis for the takeoff and landing of various carrier-based aircrafts as well as the launch of weapon system.

In practical application, several different analysis methods are generally used for extremely short-term motion prediction. Then, the optimal prediction method is determined by comparing the mean square error between the predicted value and the actual value. Finally, the extremely short-term prediction of the current navigation state is carried out. Besides, since the optimal prediction algorithm is determined by using the minimum mean square error, the true optimal algorithm may be excluded due to the phase difference. Compared with the amplitude error, the phase difference has a negligible impact on the carrier-based aircraft.

Combined with traditional theoretical prediction algorithm, the screening method for optimal extremely short-term motion prediction of ship is established on the basis of the waveform matching and affine transformation to eliminate the effect of phase difference[15]. Its implementation process is as follows.

At time t, the time history of motion signal obtained by the ship, namely the input signal of the theoretical prediction algorithm, $X(t)$, is

$$X(t)=[x(t),\ x(t-1)),\ \cdots,\ x(t-m+1)] \tag{1}$$

where m is the number of discrete signals; $x(t)$ is the motion at time t. Hence, the time history of motions at time $(t+1)$ to $(t+n)$, Y_0, is

$$Y_0(t)=[x_0(t+1),\ x_0(t+2),\ \cdots,\ x_0(t+n)] \tag{2}$$

where $x_0(t+1)$ is the obtained motion prediction value at time $t+1$ according to the input signal $X(t)$; n is the number of data points of prediction signal.

According to the input signal at time t, the time series of motion predicted by the j^{th} theoretical algorithm is

$$Y_j(t)=[x_j(t+1),\ x_j(t+2),\ \cdots,\ x_j(t+n)] \quad j=1,\ \cdots,\ l \tag{3}$$

where l is the number of prediction models.

According to the derivatives of discrete time series $Y_0(t)$ and $Y_j(t)$ [10], there is

$$f'_j(\xi)=\frac{1}{h}\left[\frac{1}{12}f_j(\xi-2)-\frac{2}{3}f_j(\xi-1)+\frac{2}{3}f_j(\xi+1)-\frac{1}{12}f_j(\xi+1)\right]+O(h^4) \quad \xi=t+2,\ \cdots,\ t+n-2 \tag{4}$$

where $f_j(t)$ is a function corresponding to $Y_j(t)$; h is the time step; ξ is the independent variable of the function and means time here.

After determining the amplitude and wave number of $Y_j(t)$, a simulation signal with the same amplitude and wave number can be obtained through affine transformation.

$$Y'_j(t)=\left[x_j(t+1\cdot c_{\text{aff}}),x_j(t+2\cdot c_{\text{aff}}),\cdots,x_j(t+n\cdot c_{\text{aff}})\right]$$
$$j=1,\cdots,l' \tag{5}$$

$$c_{\text{aff}}=\frac{\xi_{j\max}-t}{\xi_{0\max}-t} \tag{6}$$

where c_{aff} is the affine transformation coefficient.

After the affine transformation, the relative error between different prediction methods is

$$e'(j)=\frac{\sum_{i=1}^{n}\left(\left|x'_j(t+i)-x_0(t+i)\right|^2\right)^{1/2}}{n^{1/2}\cdot\max\{Y_0\}}$$
$$j=1,\cdots,l' \tag{7}$$

Hence, the optimal prediction method for ship motion under current navigation status is

$$j_{\text{optimum}}=\min\{e'(j)\};\ j=1,\cdots,l' \tag{8}$$

Accordingly, the motion postures and parameters of the ship during a short time in the future can be obtained. Besides, the model of optical landing system with ship motion can be established through coordinate conversion. Supposing the geodetic coordinate and the ship motion coordinate of the optical landing system based on Fresnel lens are $(x_g,y_g,z_g)^{\mathrm{T}}$ and $(x_s,y_s,z_s)^{\mathrm{T}}$ respectively. Hence,

$$(x_g,y_g,z_g)^{\mathrm{T}}=\begin{bmatrix}\cos\theta_s & 0 & \sin\theta_s\\ 0 & 1 & 0\\ -\sin\theta_s & 0 & \cos\theta_s\end{bmatrix}\cdot$$
$$\begin{bmatrix}1 & 0 & 0\\ 0 & \cos\varphi_s & -\sin\varphi_s\\ 0 & \sin\varphi_s & \cos\varphi_s\end{bmatrix}(x_s,y_s,z_s)^{\mathrm{T}} \tag{9}$$

where θ_s and φ_s represent the pitch angle and roll angle of a carrier-based aircraft respectively.

2 Aircraft carrier landing guidance technology

According to the equiangular glide technique, the artificial landing guidance system based on the optical beam trajectory is shown in Fig. 1. The system is mainly composed of an optical landing system, a pilot and a flight control system. Its function is that the landing system provides a stable glide beam reference under the motion of hull and deck, and then the pilot completes the landing mission through the flight control system based on the guidance of the reference beam.

Defining the vertical offset of the carrier's point on

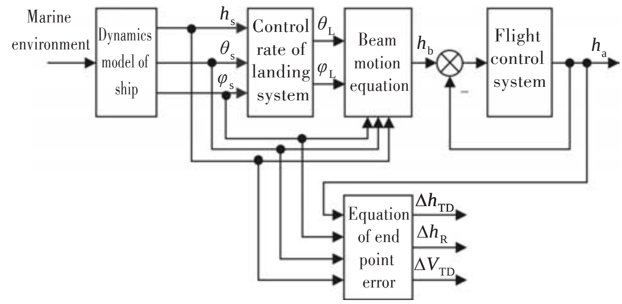

Fig.1 Block diagram of optical beam landing guidance

the actual glide reference beam relative to the ideal glide reference beam as beam motion, as shown in Fig. 2, the beam motion equation can be expressed as[16]

$$h_b=h_s+h_{\theta_s}+h_{\varphi_s}+h_{\theta_L}+h_{\varphi_L}=$$
$$[h_s+C_1\theta_s+C_2\varphi_s+C_3\varphi_L]+$$
$$[C_4\theta_s+C_5\varphi_s+C_6\varphi_L]R \tag{10}$$

where h_s, h_{θ_s} and h_{φ_s} are the changes of beam height caused by the heave, pitch and roll of hull respectively; h_{θ_L} and h_{φ_L} are the changes of optical beam height caused by the elevation and flip angles θ_L and φ_L of the lens controlled by the optical landing system, respectively; R is the distance from the point on the actual glide reference beam to the lens; C_1-C_6 are the relevant conversion coefficients[17].

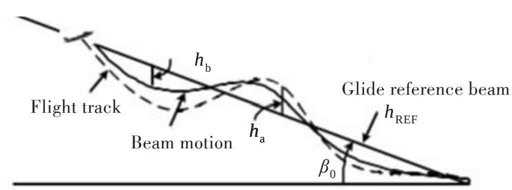

Fig.2 Tracking for optical beam motion of aircraft

When the vertical height and horizontal distance of the carrier-based aircraft to the flight deck is h_0 and x_0 respectively, and the aircraft lands with equiangular glide and ground speed of v, as shown in Fig. 3, the relationship between the ship speed U_s and the aircraft's flight track angle γ_0 is

$$\tan\gamma_0=\frac{h_0}{\dfrac{h_0}{\tan\beta_0}+U_s\cdot\dfrac{h_0}{v\cdot\sin\gamma_0}} \tag{11}$$

At any time t_i, the ideal height h_{di} of the carri-

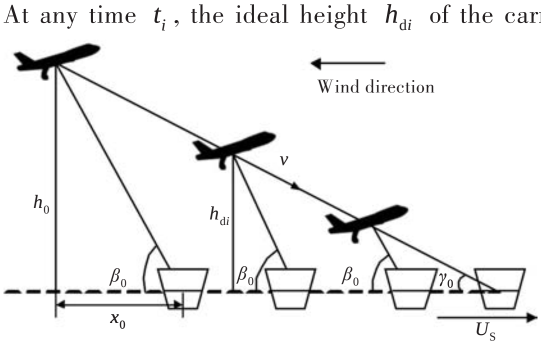

Fig.3 Schematic diagram of angle stable landing

er-based aircraft is

$$h_{di} = h_0 - \tan\gamma_0 \cdot \int_0^{t_i} v(t) \cdot \cos\gamma(t) \mathrm{d}t \qquad (12)$$

The actual height of the beam motion seen by the pilot at any time t_i is

$$h_B = h_b + h_{di} \qquad (13)$$

Because the aircraft is working under the guidance of the optical beam, in order to minimize the error of the landing end point, the pilot is required to manipulate the flight control system to make the altitude change of the aircraft h_a constantly track h_b. The three commonly used stabilization schemes of optical beam motion are inertial stability, angular stability and point stability. This paper adopts the landing guidance control scheme with angular stability. The angular stability scheme[18] simplifies the vertical motion h_{TD} of beam motion h_b relative to the ideal landing point into the corresponding translation by controlling the elevation angle θ_L and the flip angle φ_L of the lens, and the beam motion equation can be further simplified to

$$h_b = h_{TD} = h_s - L_{TD} \cdot \theta_s + Y_{TD} \cdot \varphi_s \qquad (14)$$

where L_{TD} and Y_{TD} are the longitudinal and lateral distance between the ideal landing point and the center of carrier hull motion respectively. When h_{TD} = 0, it is the ideal landing state, namely there is no relative motion and disturbance between the landing point and the inertial plane.

Thus, the control law of angular stability landing can be obtained

$$\begin{cases} \theta_L = -\dfrac{C_4}{C_6}\theta_s - \dfrac{C_5}{C_6}\varphi_s \\ \varphi_L = -\dfrac{C_1 + L_{TD}}{C_3}\theta_s - \dfrac{C_2 - Y_{TD}}{C_3}\varphi_s \end{cases} \qquad (15)$$

The landing end point error is usually used to evaluate the performance of landing guidance system. h_{aTD} is defined as the actual height of the aircraft's tail hook at the ideal landing point. The height error at the ideal landing point is defined as

$$\Delta h_{TD} = h_{aTD} - (h_s - L_{TD} \cdot \theta_s + Y_{TD} \cdot \varphi_s) \qquad (16)$$

Similarly, the impact velocity error ΔV_{TD} of the tail hook at the ideal landing point and the height error Δh_R of the tail hook at the ship bow can be obtained. Δh_R can be expressed as

$$\Delta h_R = h_{aR} - (h_s - L_R \cdot \theta_s + Y_R \cdot \varphi_s) \qquad (17)$$

where L_R and Y_R are the longitudinal and lateral distances from the center of carrier hull motion to the ship's stern; h_{aR} is the actual height from the aircraft's tail hook to the ship's stern.

According to the dynamic simulation of the time history of ship motion obtained from the extremely short-term motion prediction of ship motion, the mean square error of the end point landing error can be obtained.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} x_i^2}{n-1}} \qquad (18)$$

3 Simulation analysis of aircraft carrier landing

Taking a ship as an example, the extremely short-term motion prediction and landing process simulation are carried out. The layout of flight deck is shown in Fig. 4. The ideal landing point should be between the second and third arresting cables.

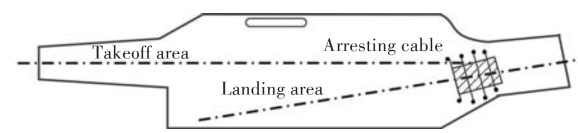

Fig.4 Layout of flight deck and arresting cable

Fig. 5 shows the time history of rolling motions of a ship and predicts the rolling motions in the next 20 s respectively with the autoregressive model based on Kalman filter (KAM method) and the Volterra series model (VR method) of Kalman filter method. The optimal prediction algorithm based on waveform matching and affine transformation is VR method, and the ship dynamics model is established according to the motion prediction results obtained by this algorithm.

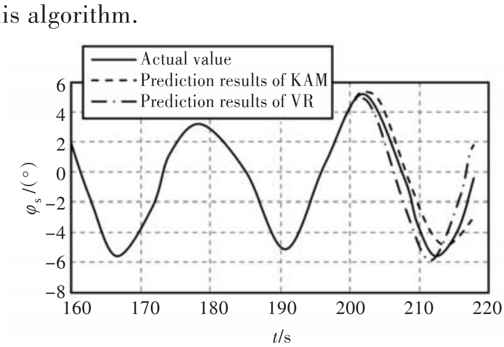

Fig.5 Time history of rolling motions and extremely short-term prediction results

On this basis, the aircraft carrier landing process is simulated, and the landing end point errors are analyzed. Fig. 6 shows the influence of ship speed on aircraft track angle. Fig. 7 shows the dynamic simulation results of angle stable optical beam riding. Fig.8 shows the landing point distribution of carrier-based aircraft. It can be seen from the simulation results that

1) The track angle of the glide landing decreases

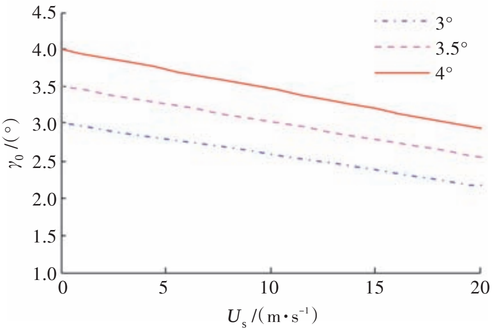

Fig.6 Influence of ship speed on aircraft track angle

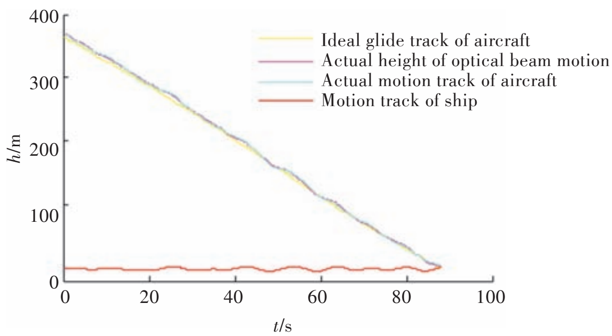

Fig.7 Simulation of angle stable optical beam riding

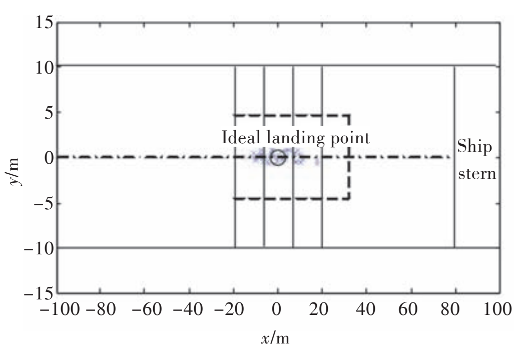

Fig.8 Landing point distribution of carrier-based aircraft

with the increase in the ship speed at the reference glide angle.

2) The landing end point errors are $\sigma(\Delta h_{TD})$ = 3.99 m, $\sigma(\Delta h_R)$ =2.47 m, $\sigma(\Delta V_{TD})$ =2.14 m/s, which satisfy the requirements of the US landing guidance system standards [19].

3) The landing points of carrier-based aircraft are relatively concentrated, most of which are located within the scope of ideal landing points, namely between the second and third arresting cables. Only a few landing points fall outside the area, so the landing safety is higher.

4 Conclusions

In this paper, the simulation model of the aircraft landing guidance control system is established in the Matlab/Simulink simulation environment. Also, the ship's extremely short-term motion prediction and the dynamic simulation of the aircraft landing are developed. According to the simulation results, the landing end point errors are analyzed, and the distribution of landing points is predicted.

The method established in this paper can more realistically consider the impact of ship motion on aircraft carrier landing. The research results can provide reference for the determination of the aircraft carrier landing method and the reasonable layout of the arresting cable.

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纵向减振推力轴承液压减振系统的热平衡性能分析

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摘　要:[**目的**]为分析活塞液压减振器稳定工作状态时的热平衡性能,解决纵向减振推力轴承液压减振系统的油路封闭且外部扰动输入未知的产热计算难题,[**方法**]将活塞摩擦损失和液压油液动损失微观产热机理的计算方法应用于液压减振系统的产热分析中,以推导出活塞振动及液压油往复流动时的功率损耗计算公式。针对具体模型的活塞摩擦产热及液动损失,计算和分析液压减振系统产热功率随振动角频率及活塞行程变化的规律。通过计算外部扰动输入功率,建立轴承部位的热学有限元模型,以得到结构的稳态温升及热流分布。[**结果**]计算结果表明,外部扰动输入功率与各部分产热功率之和大体相等,系统稳态温升较低,热流分布状况合理。[**结论**]所提产热计算方法可行,计算得到的系统近似温升在许可范围内。根据系统的热流分布图,可在热流集中部位采取相应措施来降低系统局部温升。

关键词: 液压减振系统; 摩擦产热; 液动损失; 推力轴承; 散热

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基于极短期运动预报的舰载机着舰过程仿真分析

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摘　要:[**目的**]舰载机着舰过程是其整个飞行过程中的一个关键环节,由于受到舰船运动的影响,技术难度较大。[**方法**]基于舰船极短期运动预报,开展舰载机着舰过程的仿真研究。首先,基于传统的舰船极短期运动预报方法,采用波形匹配和仿射变换,提出一种最优预报算法的确定方法;然后,建立基于光波束导引的舰载机着舰导引系统模型,并提出3个衡量着舰导引系统性能的终端误差指标;最后,开展舰载机着舰过程的仿真研究,分析舰载机对光波束运动轨迹的跟踪偏差及落点分布,得到着舰终端误差。[**结果**]由仿真结果可知,舰载机的着舰点相对集中,大多位于理想着舰点范围内,着舰终端误差满足着舰引导系统规范的要求。[**结论**]研究成果对于舰载机的着舰引导具有参考价值。

关键词: 舰载机; 着舰导引; 极短期运动预报; 落点分布; 终端误差