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Handling scheme simulation and scheduling optimization for carrier-borne aircraft

ZHENG Mao[1], *YAN Shiwei* [*2], *CHU Xiumin*[1], *ZOU Yunqi*[3], *XIE Shuo*[1]

1 National Engineering Research Center for Water Transport Safety, Wuhan University of Technology, Wuhan 430070, China;

2 The 92942 Unit of PLA, Beijing 100161, China;

3 Changjiang Waterway Bureau, Wuhan 430014, China

Abstract: [**Objectives**] To improve the deck handling efficiency of carrier-borne aircrafts, a study of rapid handling routes and scheduling schemes is carried out. [**Methods**] A fast planning method of deck handling routes based on network topology is established, and a simulation model is developed on the basis of an aircraft kinematic model and line-of-sight control method. Taking typical launching and recovery operations as examples, this paper discusses the constraints, principles, and optimization objectives of carrier-borne aircraft deck handling, and a rapid optimization method for deck handling scheduling is proposed. [**Results**] The simulation results show that the optimized algorithm can significantly shorten the total deck handling time of aviation operations, and the performance of the optimized deck handling scheme is close to the US Navy Surge Operation data in 1997. [**Conclusions**] A reasonable deck handling scheme for carrier-borne aircraft can be obtained quickly using the proposed method, which is of reference value for research into carrier-borne aircraft sortie capability and human-machine deck handling scheme decision-making.

Key words: carrier-borne aircraft; kinematic model; simulation; route planning; scheduling optimization

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0 Introduction

The deck handling scheme of carrier-borne aircraft includes two aspects including taxiing route and scheduling. A good handling scheme for carrier-borne aircraft can effectively improve the emergent sortie rate of carrier-borne aircrafts and thus ensure the survivability of aircraft carriers under the circumstances of sudden and high risk. In recent years, the US explored the optimal scheduling strategies of carrier-borne aircraft by using advanced intelligent algorithms to further improve the combat capability of aircraft carriers and developed the system of Deck Operation Course of Action Planner (DCAP) [1] to simulate the random operation events on the decks of aircraft carriers and train the machine learning algorithms to complete the optimal scheduling for carrier-borne aircrafts. The Aviation Data Management and Control System (ADMACS) of the US Navy has been equipped on aircraft carriers [2-3] to track the execution of the flight plans of carrier-borne aircrafts and visually monitor the launching and recovery of carrier-borne aircraft at the same time.

Regarding the research on the carrier-borne aircraft handling, scholars in China mainly established various mathematical models of handling routes and scheduling, using heuristic algorithms, swarm

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Authors: ZHENG Mao , male, born in 1987, Ph.D., senior engineer. Research interests: launching and recovery capability of carrier-borne aircraft. E-mail: zhmao2018@126.com

YAN Shiwei, male, born in 1982,Ph.D., engineer

***Corresponding author**: YAN Shiwei

intelligence optimization, etc., to explore and optimize the handling scheme of carrier-borne aircraft. Han et al. [4] proposed the outlines of carrier-borne aircraft with the convex hull structure and carried out the static handling route planning by taking the particle velocity of particle swarm algorithm as the taxiing velocity vector of carrier-borne aircrafts and the minimum total taxiing distance as the optimization objective. He et al. [5] introduced A* algorithm into the searching of handling routes and obtained the handling routes for rapidly entering the slide rail of catapults. Zhang et al. [6] proposed a convex hull structure based on the carrier-borne aircraft itself and the obstacle targets for the handling of decks with a rod traction system, derived the collision detection and distance computation method for multiple targets, and established the collision-avoidance route planning model with the artificial potential field method. Regarding three different kinematic models of carrier-borne aircraft such as taxiing, rodless traction, and rod traction, Liu et al. [7] established the path tracking theory for the handling of carrier-borne aircraft and ensured the accuracy of kinematic control for the automatic taxiing of unmanned aerial vehicles. For the synergetic handling of multiple carrier-borne aircraft, the handling scheduling of each aircraft is the key. Gao et al. [8] proposed an algorithm for coordinating deck handling based on mixed integer programming to solve the problems of coordination and collision avoidance in the handling process of multiple carrier-borne aircraft. Yang et al. [9] analyzed the hangar-exporting scheduling of carrier-borne aircraft and established the traffic network model of carrier-borne aircraft. The heuristic searching optimization for the scheduling scheme was performed to maximize the utilization rate of personnel and equipment. Taking the shortest total handling time and distance as the optimization objectives, Si et al. [10] used the particle swarm algorithm and genetic algorithm to obtain the optimal layout and handling scheduling of carrier-borne aircraft respectively.

In practice, the handling schemes are manually arranged in advance by the commander in other countries currently. During this process, auxiliary devices such as Ouija board and command telephone are used for commands, which can achieve a good handing effect for the scenarios with a small number of carrier-borne aircraft. However, regarding the arrangement of complex and concurrent handling scheme for the launching of aerial fleet, the handling schemes show difficulties and have insufficient robustness to random events.

To sum up, the heuristic searching is mainly adopted in the current determination of handling routes and scheduling optimization of carrier-borne aircraft. It is of low computational efficiency and is difficult to obtain the optimal handling scheme quickly, especially for the concurrent launching and recovery of multiple aircraft.

Therefore, taking the carrier-borne aircraft on USS Gerald R. Ford as research object, this paper introduces the network topology structure of graph theory into their operation procedures of launching and recovery, the initial layout form, the handling principles, and the constraint conditions in hope of achieving a rapid planning of handling routes. Moreover, the paper establishes the kinematic model of taxiing for carrier-borne aircraft and realizes the precise trajectory control with the line-of-sight (LOS) method. A generation and optimization method for rapid handling scheduling is proposed for the synchronous and concurrent handling operations of multiple aircraft. As a result, high computational efficiency is achieved on the premise of ensuring the shortest total handling time of the specified number of carrier-borne aircraft.

1 Handling route planning based on network topology structure

1.1 Directed and multi-value network

Topology network is an important tool for network structure analysis and route planning, and there are many types of networks. The routes between nodes need to be weighted for network structures sensitive to the traffic flow and distance, such as the handling routes of carrier-borne aircraft. At the same time, considering that the taxiing process of carrier-borne aircraft cannot be reversed, so the directed multi-value network should be adopted to represent the handling of taxiing routes. On this basis, the algorithms such as Dijkstra and Warshall-Floyd can be used to quickly obtain the handling and collision avoidance routes.

In the actual deck handling of carrier-borne aircraft, the "relay type" handling command is conducted by several regions, and each region has several handling crews who are specifically responsible for the handling command of carrier-borne aircraft in the region, which has the relatively fixed handling routes. This approach has the following advantages: First, the handling route consists of multiple routes end to end, which is relatively fixed, greatly reduces the uncertainty, and thereby shortens the time for route planning. Second, the handling scheme can be delivered conveniently, and the handling crews can understand the handling scheme more accurately. On the flight deck that is full of random events, "being slow does not matter but standing does, " and "the certainty is efficiency, " which indicates that trying to reduce the uncertainty in the handling process is the key to ensuring the handling efficiency.

1.2 Network topology of the deck handling for carrier-borne aircraft

Definition: If there is a direct route r between route nodes i and j, the route r_{ij} is defined as a route element, which means that the route from node i to node j is unobstructed unidirectionally. The straight-line length of the route element is its distance. The elements of the adjacency matrix can be expressed as follows:

$$a_{ij} = \begin{cases} 1, & \exists r_{ij}(i, j \in [1, N]) \\ 0, & \exists r_{ij}(i, j \notin [1, N]) \end{cases} \tag{1}$$

The elements of the distance matrix are shown below:

$$l_{ij} = \begin{cases} \|pos(i) - pos(j)\|, & \exists r_{ij}(i, j \in [1, N]) \\ \text{inf}, & \exists r_{ij}(i, j \notin [1, N]) \end{cases} \tag{2}$$

where $pos(i)$ and $pos(j)$ are the coordinates of route nodes i and j, respectively; $\|\cdot\|$ is the straight-line distance between the two route nodes.

Taking the USS Gerald R. Ford as the research object, we adopt the starting and ending points of the handling such as the aircraft support position, the temporary aircraft stands, and the launching point as the directed route nodes, the turning points during taxiing as the undirected route nodes, as shown in Fig. 1. The handling route nodes are determined for the actual handling routes of carrier-borne aircraft under typical operations such as launching and recovery. We obtain the adjacency matrix and distance matrix by judging one by one whether any two route nodes are directly connected.

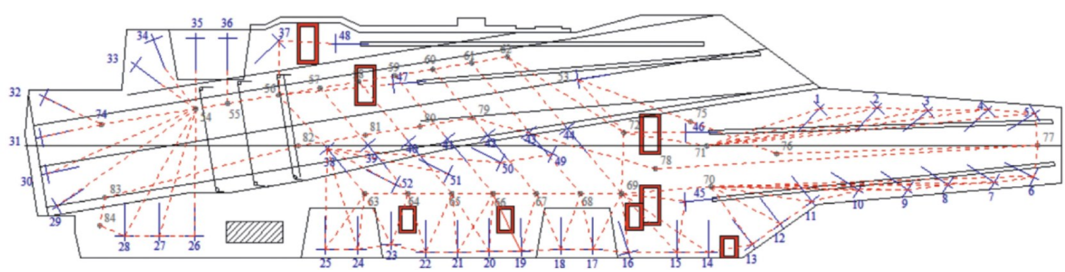


Fig. 1 Deck handling network topology for USS Gerald R. Ford

1.3 Handling route planning and collision avoidance policies

The shortest route is selected as the objective of handling route planning, and the Warshall-Floyd algorithm is used to search and obtain the node sequence of the optimal handling route. In searching for the shortest route, this algorithm has the advantages of low computational complexity and simultaneous search of all route nodes, which is thus convenient to improve the computational efficiency.

For the collision detection and the automatic collision avoidance strategy during multi-aircraft handling, the taxiing maneuverability of carrier-borne aircraft is poor in the actual handling and the distance from a carrier-borne aircraft to its neighbor is fairly limited. When the distance between two carrier-borne aircrafts is less than the safety threshold, one carrier-borne aircraft needs to wait for the other one to pass through before continuing to taxi instead of re-planning the new collision avoidance route. Under the principle of simplifying the calculation without losing accuracy, the center of the smallest outer circle of the carrier-borne aircraft is used as the centroid, and the distance between the centroids of carrier-borne aircraft m and n is defined as D_{mn}, as shown in Fig. 2. When D_{mn} is less than the safety threshold, the distance between the current positions of two aircrafts and the intersection node of their taxiing routes are calculated re-

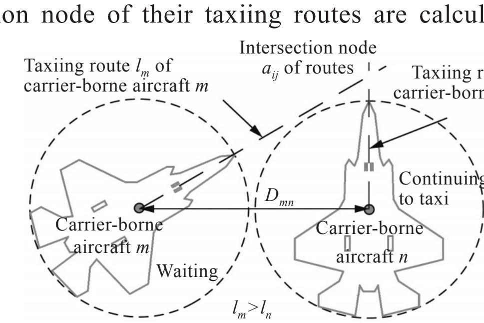


Fig. 2 Collision avoidance policies for carrier-borne aircraft

spectively. The aircraft closer to the intersection node can taxi through first. The other one continues to taxi after the distance between this two aircrafts is greater than the safety threshold.

2 Simulation of carrier-borne aircraft deck handling

The aforementioned content expounds the network topology structure and the sequence of optimal route nodes for the deck handling of carrier-borne aircraft. On this basis, the kinematic and control model for taxiing of carrier-borne aircraft can be established.

2.1 Kinematic model for carrier-borne aircraft taxiing

The force acting on the carrier-borne aircraft during taxiing can be decomposed into forward engine thrust, air resistance, rolling resistance of the wheel, and lateral frictional resistance of the wheel. Assuming that the nose wheels of carrier-borne aircraft only have rolling friction without lateral taxiing, the horizontal position and heading of the carrier-borne aircraft can be expressed according to geometry, as shown in Fig. 3.

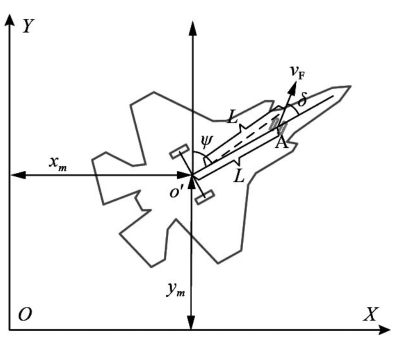


Fig. 3 Kinematic model for carrier-borne aircraft taxiing

The global coordinate system XOY of the deck is established. The wheel base (the distance between the nose wheel and the main wheel) is set as L, and the midpoint of the connecting line between the main wheels is o'. Besides, the heading of the carrier-borne aircraft ψ is the angle between the heading and the Y axis in positive direction; the turning angle of nose wheel A is δ (which is positive when the nose wheel turns right); the taxiing speed of the nose wheel is v_F. Then the speed of the midpoint o' of the connecting line between the main wheels can represent the taxiing speed v of the carrier-borne aircraft. Hence, the kinematic state $\boldsymbol{X}_m = [x_m, y_m, v_m, \psi_m, \delta_m]^T$ of carrier-borne aircraft m can be written as the following differential equation of motion.

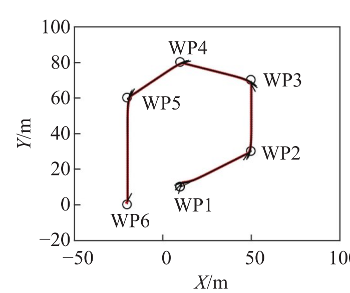
$$\frac{\mathrm{d}\boldsymbol{X}_m}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} x_m \\ y_m \\ v_m \\ \psi_m \\ \delta_m \end{bmatrix} = \begin{bmatrix} v_m \sin(\psi_m) \\ v_m \cos(\psi_m) \\ v_F \cos(\delta_m) \\ -\arcsin(v_F \sin(\delta)/L) \\ \mathrm{d}\delta_m \end{bmatrix} \tag{3}$$

where $\mathrm{d}\delta_m$ is the steering angular velocity of the nose wheel of the carrier-borne aircraft. To simplify the simulation complexity without losing the accuracy of the handling scheme, we assume the taxiing speed v_F of nose wheel to be a constant, which can be generally determined by statistical results. The real-time parameters such as the position, the taxiing speed, and the heading of the carrier-borne aircraft can be obtained with the differential equation [Eq. (3)].

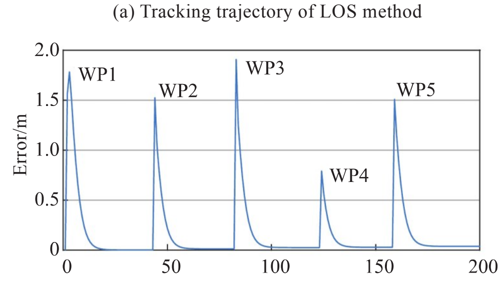
2.2 Kinematic model based on the LOS method

To control the taxiing trajectory of the carrier-borne aircraft close to the planed route, the LOS method is introduced to analyze the position deviation and the heading of carrier-borne aircraft in real time [11], and the LOS angle (ϕ_{LOS}) of carrier-borne aircraft is solved to determine whether it is close to a way point and switches to the next way point. The controlling objective of the turning angle of the nose wheel is $\delta = \phi_{LOS} - \psi$.

By solving the kinematic differential equations and using the LOS method for trajectory tracking control, one can make the carrier-borne aircraft start from the initial position, pass through WP1–WP5, and finally reach WP6, as shown in Fig. 4(a). The tracking errors mainly occur at the moment when the target way point is switched, with the maximum



(a) Tracking trajectory of LOS method



(b) Tracking trajectory error of LOS method

Fig. 4 Results of LOS controlling method error not exceeding 2 m. The target route can be returned to in about 10 s. The above indicates good accuracy of control, as shown in Fig. 4(b).

Because the start and end points of carrier-borne aircraft taxiing are all predefined aircraft stands, which belong to the directed route nodes and can only be parked in accordance with the aircraft stands. Therefore, a temporary undirected route node is added at the directed route nodes (aircraft stands) in the taxiing direction to smoothen the getting in and out of the taxiing paths at directed aircraft stands.

3 Multi-aircraft deck handling simulation and scheduling optimization method

3.1 Multi-aircraft deck handling simulation

After the determination of the shortest handling route between the current position of each carrier-borne aircraft and the target position of handling, the computer program of handling simulation is developed to achieve the rapid multi-aircraft simulation.

The handling simulation program implements the simultaneous multi-aircraft handling scheme simulation by many calculations such as the sequence planning of optimal route nodes and the solution of kinematic differential equations, LOS trajectory tracking control, automatic collision avoidance and waiting, and graphical display. The detailed flowchart is shown in Fig. 5. In this paper, the optimization methods of handling scheduling for launching and recovery operations are respectively discussed.

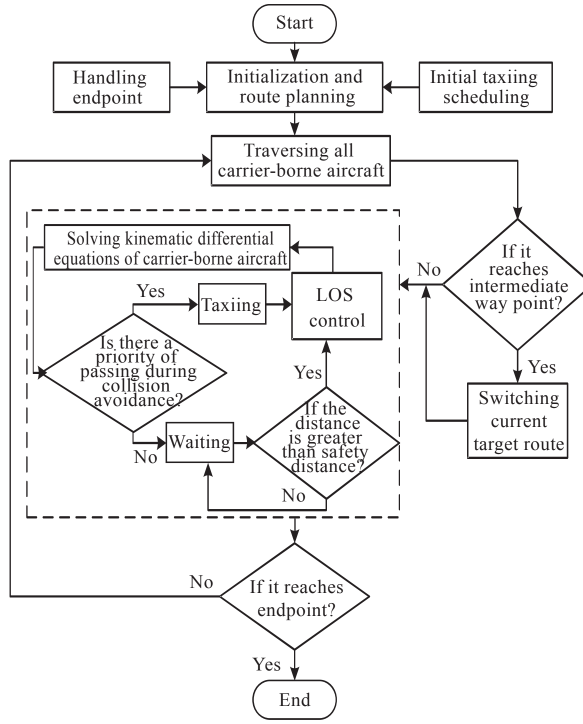


Fig. 5 Flowchart of multi-aircraft deck handling simulation

3.2 Optimization method for the handling scheduling of launching operation

In the actual handling operation, scheduling is the key to ensuring the handling efficiency, which is constrained by many factors. This paper proposes a rapid optimization method for handling scheduling. Herein, the handling of launching is taken as an example. Multiple carrier-borne aircrafts depart from different aircraft stands and respectively taxi to different catapults. Thus, this process involves the virtual queue problem of correspondence of multiple catapults to carrier-borne aircraft. In practice, this kind of concurrent operation results in complex situations such as crossed taxiing routes and delays for different queues of carrier-borne aircraft, which is a typical complex handling scenario.

On the premise that the target catapult corresponding to each aircraft stand is determined, the design variable of the optimization algorithm of handling scheduling is the initial taxiing time of each carrier-borne aircraft standing by.

The constraint conditions of deck handling can be summarized as follows:

1) The carrier-borne aircrafts need to taxi independently from the aircraft start position to the launching position, which can only taxi forward and not backward.

2) When the 3# catapult of USS Gerald R. Ford has a carrier-borne aircraft, the 4# catapult is not allowed to carry out the launching operations and the launch bar of carrier-borne aircraft is not attached.

3) The preparing time for launching at the position of catapult-assisted take-off obeys the normal distribution.

4) The number of carrier-borne aircraft handled at the same time shall not be greater than the total number of handling crews.

5) The safety spacing between two carrier-borne aircrafts is the circumscribed circle diameter of the plane outline.

On the premise of satisfying the above constraint conditions, the following principles are followed to develop the scheduling optimization for multi-aircraft handling:

1) During the launching operation, the carrier-borne aircraft closer to the catapult is given priority to start taxiing.

2) The priority of early warning aircraft is higher than that of fighters.

3) The carrier-borne aircraft parked on the landing deck launch preferentially.

4) The idle/waiting time of catapults should be shortened as much as possible to improve their utilization rate.

The shortest total time of launching and handling operation is taken as the objective of handling scheduling optimization and the following optimization objective function is established:

$$J = \min[(T_{\mathrm{S},m} + t_m + t_{\mathrm{CATA},m}) | m \in 1,2,\cdots,M] \quad (4)$$

where $T_{\mathrm{S},m}$, t_m, and $t_{\mathrm{CATA},m}$ are respectively the moment of starting taxiing, handling time, and the preparing time of catapults for the m-th carrier-borne aircraft.

The optimization method proposed in this paper is divided into three steps to achieve the above optimization objectives, namely the load distribution of catapults, the inversion of starting-taxiing moment, and the compression of handling time. The optimization can also be called as "three-step method" .

1) Load distribution of catapults.

When multiple catapults synchronously launch carrier-borne aircrafts, the operation load of each catapult should be equally distributed and the sequence of carrier-borne aircrafts corresponding to each catapult should be reasonably arranged so that the total launching operation time can be shortened. According to the ranking of the shortest distance of route from the initial aircraft stand of carrier-borne aircraft to each catapult, the nearest catapult is determined for each carrier-borne aircraft. In this way, the preliminary distribution of carrier-borne aircraft is completed. When multiple catapults synchronously work, the situation that the distribution of some carrier-borne aircrafts is concentrated on one catapult may exist. At this point, the carrier-borne aircraft farther away from the catapult are formed into a new set and further distributed to other catapults from the near to the distant. This makes the number of carrier-borne aircrafts distributed to each catapult approximately equal.

2) Inversion of starting-taxiing moment.

Assuming that each catapult launches the carrier-borne aircraft uninterruptedly for the maximum utilization rate of catapults, the launch sequence is known. Then the moments of carrier-borne aircrafts starting taxiing can be obtained by the inversion of the launching moments. For the carrier-borne aircraft distributed to each catapult, the distance to the catapult is sorted from small to large, and the carrier-borne aircraft closer to the catapult has priority to start taxiing. The starting time of total carrier-based aircraft launching operations is set as T_0 and the starting time of taxiing of the m-th carrier-borne aircraft corresponding to the i-th catapult is T_{im}. Then the launch time of each carrier-borne aircraft distributed to the i-th catapult can be expressed as follows:

$$T_{\mathrm{L}im} = T_{im} + t_{im} + t_{\mathrm{CATA},im} = T_0 + \sum_{m \in \Omega_i} t_{\mathrm{CATA},im} \quad (5)$$

where t_{im} is the handling taxiing time of the m-th carrier-borne aircraft distributed to the i-th catapult; $t_{\mathrm{CATA},im}$ is the preparing time for launching of the aircraft; Ω_i is the set of carrier-borne aircrafts distributed to the i-th catapult. Therefore, the starting-taxiing time of the aircraft can be inverted by Eq. (5):

$$T_{im} = T_0 + \sum_{m \in \Omega_i} t_{\mathrm{CATA},im} - t_{im} - t_{\mathrm{CATA},im} \quad (6)$$

3) Compression of handling time.

By the inversion of the starting time of taxiing, the "single-line" handling scheduling planning without crossed routes can be completed well. However, for the situation that multiple catapults release the carrier-borne aircraft synchronously, the taxiing routes of multiple carrier-borne aircraft may intersect and the current carrier-borne aircraft needs to wait for the previous carrier-borne aircraft to pass through before continuing the taxiing, which disrupts the original scheduling and increases the randomness. For the purpose of reducing the possibility of jam on the deck, the starting-taxiing time of the latter carrier-borne aircraft should be delayed to avoid further jam due to waiting at the center of the flight deck during the taxiing process. Supposing the time for the m-th carrier-borne aircraft to wait for the n-th carrier-borne aircraft is t_{W,n_m}, the starting-taxiing moment of the m-th carrier-borne aircraft needs to be delayed by t_{W,n_m}, and so forth. The starting-taxiing moments of all subsequent carrier-borne aircrafts using this catapult needs to be delayed by t_{W,n_m}. To avoid the possibility of collision with other carrier-borne aircrafts caused by the delay of the starting-taxiing moments, we adopt the compression of handling time and inversion of starting-taxiing moment several times in combination with the handling simulation. Generally, the continuous and reasonable handling scheduling scheme with the shortest handling time can be obtained after 2−3 times of processing.

3.3 Optimization method for the handling scheduling of the recovery operation

During the recovery operation, the carrier-borne aircrafts land on the front of the angled deck with the frequency of one carrier-borne aircraft per minute and then taxis to the aircraft stands at bow and starboard. The handling principles can be sorted out as follows:

1) The priority order of the target aircraft parking area after landing is as follows: the port side of the bow parking area > the starboard side of the bow parking area > the middle of the starboard side > the left front of the island > the rear of the island.

2) The parking order in each parking area is designated in advance from far to near according to the taxiing route.

Because there is only one initial position for recovery operation and only one aircraft can be recovered per minute, the possibility of intersection and collision of multi-aircraft taxiing routes does not exist. Hence, the handling scheduling scheme of recovery operation can be realized according to the point-to-point handling simulation of single aircraft.

4 Verification of simulation experiment

4.1 Software development of rapid simulation of deck handling

The program of rapid stimulation of deck handling for carrier-borne aircraft is developed with Matlab 2016b GUI, and human-machine graphical operation interface is developed. It has several functions such as the route node setting of deck handling, the auxiliary generation of arrangement planning for carrier-borne aircraft, the automatic distribution of catapults for carrier-borne aircraft, the automatic optimization of handling scheduling, with the ability of handling stimulation at the speed of 1 to 100 times. At the same time, the program supports the parameter settings such as the distribution of preparing time for catapult-assisted take-off, available catapults, and random catapult failure.

Considering that the actual handling process lasts for several hours, a timer is used to balance the task distribution between the simulation control of the carrier-borne aircraft taxiing and the generation of simulation animation to ensure the consistency and timeliness of the program and achieve the rapid handling to save the simulation time. Notably, the optimization calculation of handling scheduling does not involve the drawing of simulation animation, and thus the optimization is completed within 1 s.

4.2 Handling scheme simulation of typical launching and recovery operations

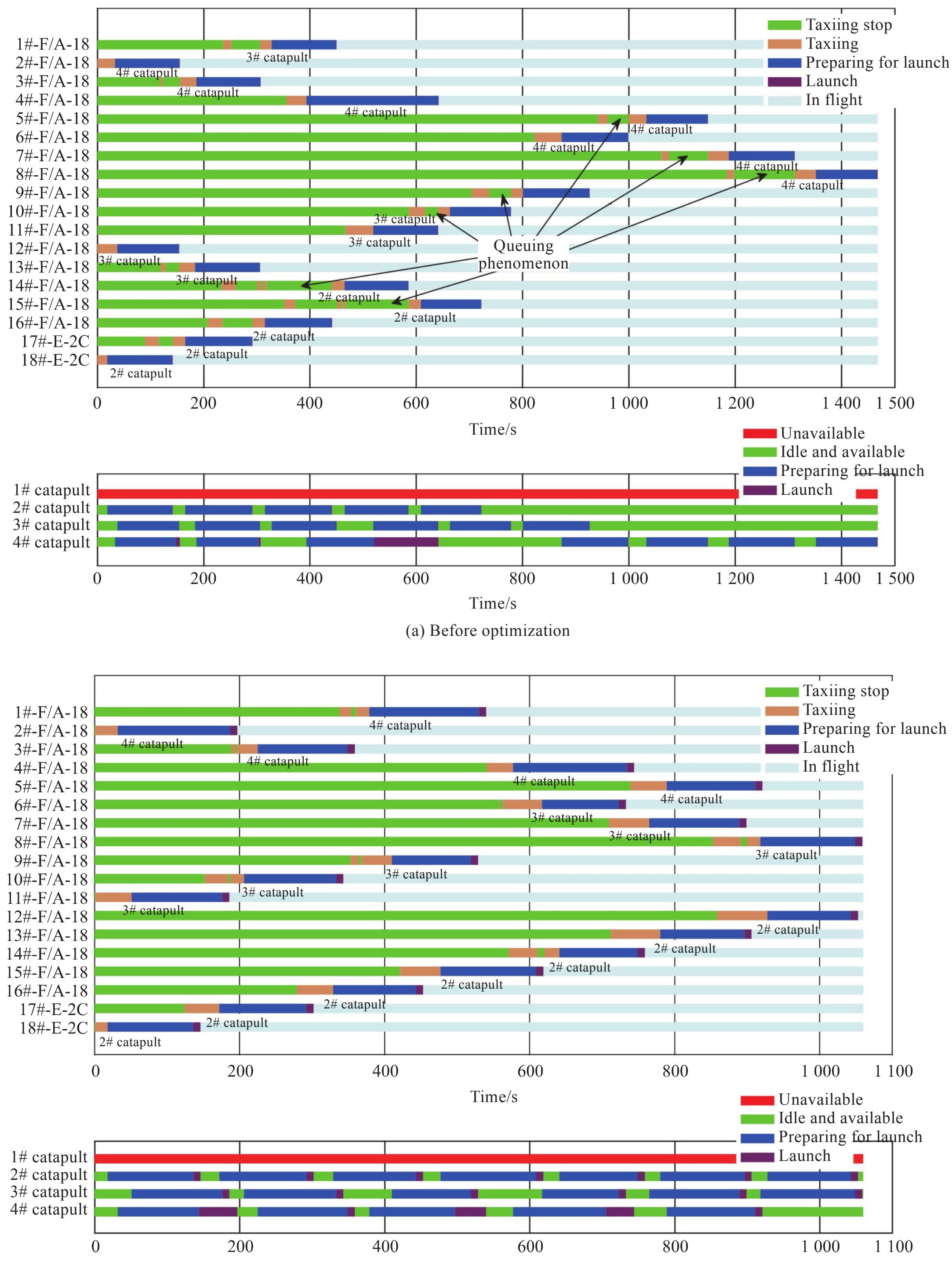
The launching and recovery operations of 18 aircrafts are simulated with the above software, with the simulation parameters listed in Table 1 and the initial states shown in Fig. 6. The 18 aircrafts are mainly parked on the starboard side, the rear of the ship island, the rear of the port side, and the rear of the landing runway. Under the condition that only the principle of proximity is used to arrange the launching scheduling of carrier-borne aircraft, the 18 aircrafts are launched by three catapults within total time of 24.25 min. As shown in Fig. 7(a), 2# and 3# catapults are idle after 920 s, and the carrier-borne aircrafts are mainly launched by 4# catapult. This indicates that the load difference of catapults is large, and the queuing phenomenon is distinct. The probability density (Fig. 8(a)) and the probability distribution (Fig. 8(b)) of the launching interval are investigated. In Fig. 8(a), the green histogram indicates the occurrence number of launching interval for carrier-borne aircraft, and the blue curve shows the fitting result. By comparing with the statistics during the Surge Operation exercise of the US Navy in 1997, it is found that the launching interval in simulation is longer and the probability distribution curve is gentler.

The total handling time is reduced to 17.52 min by automatic optimizations such as the distribution of catapults, the inversion of starting time of taxiing, and the compression of handling time (Fig. 7(b)). The idle time of three catapults is greatly reduced. The operation load of each catapult is more balanced, and the utilization rate of catapults is high. Due to the more balanced launching operation load

Table 1 Parameters setting of handling simulation

Parameter	Set value
Taxiing speed v_f nose wheel, m·s^{-1}	2
Aircraft type	F/W-18, E-2C
Average preparing time for launch, s	120
Variance of preparing time for launch, s	20
Available catapults	2#, 3#, and 4# catapults

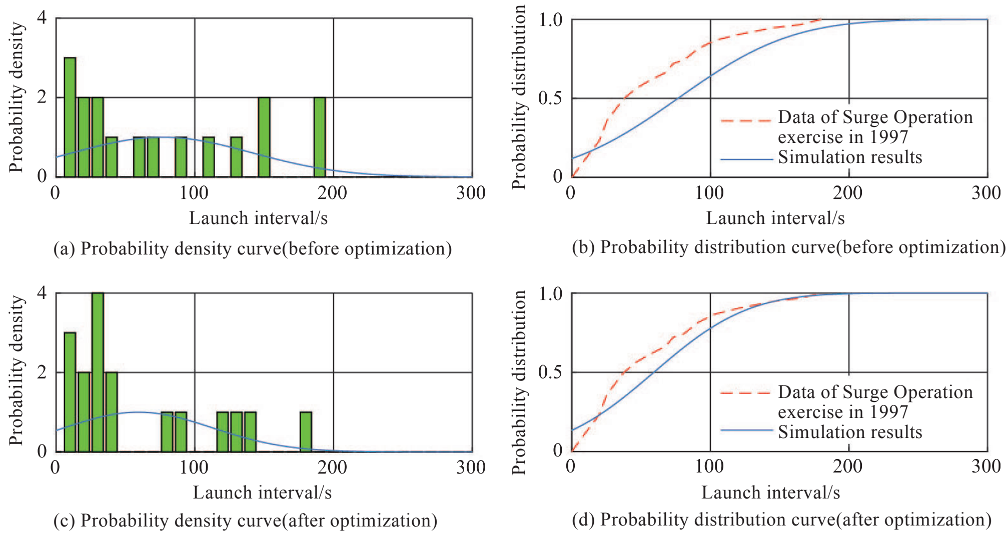
Fig. 6 Initial state of launching operation for 18 aircrafts



(a) Before optimization

(b) After optimization

Fig. 7 Gantt-chart of launching operation deck handling for 18 aircrafts



(a) Probability density curve(before optimization)
(b) Probability distribution curve(before optimization)
(c) Probability density curve(after optimization)
(d) Probability distribution curve(after optimization)

Fig. 8 Statistics of the interval time for launching

of 3# and 4# catapults, their operation rhythm is more consistent, and the overall time of launching is shortened (Fig. 8(c)). The distribution of launching interval of the handling stimulation after the scheduling optimization is similar to the statistical curve of the US Navy Surge Operation. Namely the launching efficiency is close to that of the US Navy (Fig. 8(d)).

After the completion of recovery operation, the arrangement states of 18 aircrafts on the flight deck are shown in Fig. 9. The time for carrier-borne aircraft taxiing from the landing runway to the target aircraft stand is between 30 and 90 s, and the total time for the recovery and handling of all 18 aircrafts is 17.48 min. As presented in Fig. 10, the target aircraft stands involve the port and starboard sides of bow and the left front of the island, and all carrier-borne aircraft voluntarily taxi into the aircraft stands.

Fig. 9 Final state of recovery operation for 18 aircrafts

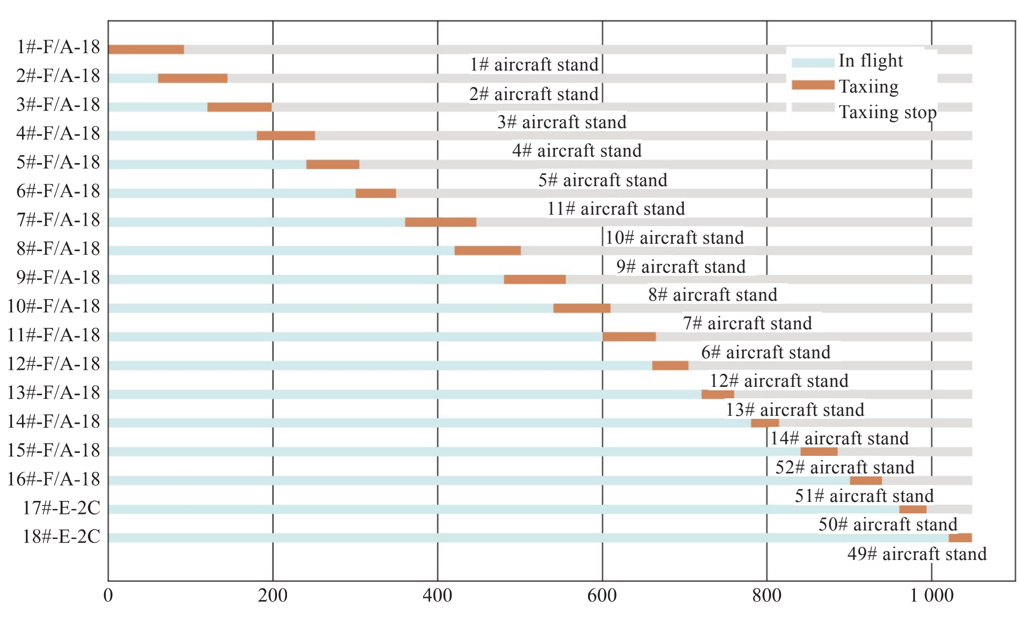


Fig. 10 Gantt-chart of recovery operation deck handling for 18 aircraft

5 Conclusions

This paper takes the USS Gerald R. Ford as the research object and has developed a model of deck handling simulation and scheduling optimization for carrier-borne aircraft. The corresponding simulation software is developed to assist the crews in completing the rapid planning of handling scheme. For the launching and recovery operation for carrier-borne aircraft, a good optimization effect is achieved. Specific conclusions are as follows:

1) The established network topology for deck handling can be used for rapid planning of handling routes of carrier-borne aircrafts, which conforms to the characteristics of the actual handling route.

2) The established kinematic model of carrier-borne aircraft and the LOS control method can realize the kinematic simulation of carrier-borne aircraft taxiing.

3) The launching operation of carrier-borne aircraft involves the concurrent operation of multiple queues of catapults and carrier-borne aircraft, which is difficult to optimize. The "three-step method" can effectively express the handling principle and achieve the rapid handling scheduling optimization, thereby shortening the total handling time and having a very high planning efficiency.

4) The recovery operation of carrier-borne aircrafts belongs to the "single-thread" handling and almost does not involve the problems of intersection and collision avoidance between multiple carrier-borne aircrafts. The generation of automatic handling scheme is easier for it.

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舰载机典型调运方案推演与时序优化

郑茂[1], 颜世伟[*2], 初秀民[1], 邹运其[3], 谢朔[1]

1 武汉理工大学 国家水运安全工程技术研究中心，湖北 武汉 430070

2 中国人民解放军92942部队，北京 100161

3 长江航道局，湖北 武汉 430014

摘　要：［目的］为提高舰载机甲板调运效率，开展舰载机调运路径与时序的快速规划研究。［方法］建立一种基于网络拓扑结构的调运路径快速规划方法，引入舰载机运动模型和轨迹跟踪控制方法，建立仿真推演模型。以典型出动回收作业为例探讨舰载机调运约束条件、调运原则以及优化目标，提出一种调运时序快速优化方法。［结果］仿真推演结果显示，优化算法可提高多台弹射器作业进程的并行度，优化后的调运方案与1997年美军高强度演习数据接近。［结论］运用所提出的方法可快速获得真实合理的舰载机甲板调运方案，对于舰载机出动回收能力研究、调运方案辅助决策具有参考价值。

关键词：舰载机；运动模型；仿真；路径规划；时序优化