Optimized ship resilience under multi-wave attack based on genetic algorithm

Zuodong Wu[a], Cuiyun Zhu[b], Zhen Li[*c]
[a]The First Military Representative Office of the Naval Equipment Department in Shanghai, Shanghai 201913, China; [b]Jiangsu Automation Research Institute, Lianyungang 222061, Jiangsu, China; [c]Ocean College, Jiangsu University of Science and Technology, Zhenjiang 212003, Jiangsu, China

ABSTRACT

Due to the complexity of the battlefield environment at sea and the diversity of attack forms, a single fixed maintenance strategy cannot cope with the varied attack modes of the enemy at all times after the ship system is attacked. Aiming at the marine battle environment, this paper simulates the multi-wave attack chain and ship defence system, so that the ship equipment node has different wartime importance according to different combat environment, combined with the explosion and damage model, interception and confrontation model. The repair sequence of damaged nodes under multiple constraints was abstracted to the path planning problem similar to MSTP, and an Attack Defence Recovery Strategy (ADRS) was proposed by combining adaptive genetic algorithm with the wartime importance of equipment nodes. Experiments simulation has been taken under the same constraints and multi-wave enemy attack with different recovery strategy system of confrontation and resilience recovery. The results show the system resilience recovery based on ADRS is effective under the waves of attacks, reduces system damage, improves the system robustness, and especially greatly increases under relatively severer damage.

Keywords: Genetic algorithm, optimization, resilience, path planning

1. INTRODUCTION

With the rapid development of high and new technologies, the form of war has evolved into a five-in-one joint operation, including sea, land, air, space and electromagnetic[1]. Therefore, multi-wave attack of the same type or even multi-wave and multi-type has become one of the common combat modes at sea. The widely accepted definition of a resilient system, proposed by the U.S. Department of Defence, is that a resilient system performs its duties and functions well in a variety of environments[2], is easily adaptable to many other systems through reconfiguration or replacement, and has a moderate and detectable decline in function. In the multi-wave combat environment, the system faces not only one damage, but multiple damages. The resilience of the system is not reflected in the recovery after attack, which is slightly passive, but should be more active to reduce the damage in the whole process of multi-wave damages.

In Section 1, the concept, recovery and measurement of resilience system and the basic concepts of the Multiple Traveling Salesmen Problem (MTSP) are introduced. In Section 2, the components and basic concepts of the models are introduced. Section 3 introduces the basic concept and algorithm principle of ADRS. Finally, in Sections 4 and 5, the advantages of ADRS are compared and analysed from multiple types of wave attacks, and the conclusion is that the advantages of ADRS can be better reflected in the relatively harsh combat environment, improve the robustness of the system, and make the system have better resilience.

2. BASIC CONCEPTS AND METHODS

2.1 Resilient systems and their recovery

From an engineering point, resilience has been regarded as an important property of the system, that is, the ability of the system to recover its basic function from the damaged state after the system is physically damaged or beyond the range of its defence capability due to attack. System resilience refers to the ability of the system to recover the lost performance after the failure event[3]. A good recovery strategy can restore the system to the best performance level within a certain

[*] justlz@just.edu.cn

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period of time after being disturbed. There are two main recovery methods: external equipment repair and internal reorganization.

Maintenance is all the activities carried out to maintain, restore or improve the specified technical state of the system[4]. Therefore, the establishment of maintenance strategy is the most important, a good military system maintenance strategy can make their own economic, personnel and combat readiness material loss to minimize, and regain the initiative of the battlefield. Facts have proved that in small regional wars with advanced information technology, the conditions of preparing for war are compressed and the process of war is greatly accelerated. Maintaining the combat effectiveness of troops will be more dependent on the maintenance and support of defence systems.

Quotient Resilience Model

System resilience is defined as the ratio between the recovery value and the loss value of the system node efficiency, that is, the ratio between the recovered node efficiency level and the reduced efficiency level is used to measure the resilience change[5]:

$$R(t) = \frac{Recovery(t)}{Loss(t_d)} \tag{1}$$

where, $R(t)$ is the system resilience at time *t*, known as quotient resilience model; $Recovery(t)$ is the node efficiency level recovered at time *t*; $Loss(t_d)$ is the loss value of system node efficiency.

Equation (1) shows the ability of the system to recover from interference events. If the system recovers to its initial state, that is, $Recovery(t) = Loss(t_d)$, the system is fully elastic. On the contrary, if there is no recovery value, that is, $Recovery(t) = 0$, then the system shows no resilience.

Given the performance measurement $\varphi(t)$, interference event e^j, interference event occurrence time t_e, recovery start time t_s, recovery completion time t_f, the system resilience during the whole performance change process can be expressed by the following formula

$$R_Q(t|e^j) = \frac{\varphi(t|e^j) - \varphi(t_d|e^j)}{\varphi(t_0) - \varphi(t_d|e^j)}, \quad t > t_s \tag{2}$$

where, $R_Q(t|e^j)$ is the quotient resilience of the system at time *t* after the occurrence of interference event e^j, $\varphi(t|e^j)$ is the performance of the system at time *t*, $\varphi(t_d|e^j)$ is the performance after system degradation under interference event e^j. In equation (2), the denominator represents the degradation degree of system performance after the occurrence of interference events, and the smaller the value, the better the resilience. The numerator represents the performance level that the system can recover under the action of the recovery strategy, and the larger the value, the better the resilience. The values of numerator and denominator reflect the influence of interference events and recovery strategy on system performance in the process of resilience recovery.

MTSP and Genetic Algorithm

MTSP problem belongs to NP-Hard combinatorial optimization problem[6], which is characterized by discrete, grouped parallel and multi-objective optimization, making heuristic algorithm widely used in MTSP problem[7]. Trigui et al.[8] regard the task allocation problem of multi-robot as MTSP model, and take the maximum driving distance and the total driving distance as the optimization objectives to transform the multi-objective optimization problem into a single-objective optimization problem. When Zhang et al.[9] solved the underwater AUV path planning problem, energy consumption and energy balance were taken as the double costs of the multi-traveling salesman problem, and the MTSP-GA algorithm model was used to output the AUV path under three-dimensional coordinates.

Genetic Algorithm (GA) is based on the theory of evolution and heredity. The theory of natural selection in the theory of evolution says that the emergence of species is the inevitable result of natural selection. Those with the best adaptation survive and reproduce, while those with the worst will be weeded out. Wang[10] used genetic algorithm to solve the problem of substation fault recovery, and obtained a reasonable switch operation table with the goal of minimizing the cost of equipment operation and non-fault power failure area, so as to complete the isolation of fault area and normal power supply in non-fault power failure area. Jiang et al. studied ship power system faults and proposed an adaptive GA recovery strategy based on cloud theory[11]. This method will load and switch by priority is divided into multiple objective function, and considering the equilibrium line load distribution, with the analytic hierarchy process to integrate into the comprehensive objective function, and then adopt cloud theory of adaptive genetic algorithm to solve the model.

3. BASIC CONCEPTS AND METHODS

3.1 Enemy attack model

There are many attack modes at sea. In this study, three attack types, small UAV in low altitude, aircraft/missile in high altitude and torpedo underwater, are selected as simulation objects according to the explosive yield and interception difficulty of weapons from small to large. According to different attack types, the enemy attack matrix with multiple wave times including different explosive equivalent and landing point is constructed. In this study, the enemy is proposed to launch 5 waves of attack, with an attack interval of 30 minutes, and each wave contains an unknown type of attack, as shown in the matrix below.

$$T = \begin{pmatrix} T_1 \\ T_2 \\ T_3 \\ \vdots \\ T_n \end{pmatrix} \tag{3}$$

$$T_* = \begin{pmatrix} n_1 & tnt_1 & x_1 & y_1 & z_1 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ n_3 & tnt_3 & x_3 & y_3 & z_3 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ n_5 & tnt_5 & x_5 & y_5 & z_5 \end{pmatrix} \tag{4}$$

In the formula above, T_n represents *n*-wave attack, including attack serial number, attack equivalent and attack landing point information. The serial number n determines the type of attack, 1-10 for high-altitude aircraft/missiles, 11-20 for low-altitude drones, and 21-30 for underwater torpedoes.

3.2 Ship defense system

Ship defence system includes three-dimensional coordinates and node types of system nodes. In order to meet the concept that node importance varies in different combat environments, this study assigns different wartime tasks according to node types and establishes different importance degrees in different combat environments. The node information is shown in Table 1.

Table 1. Node information.

Type of node	Number of node	Tasks and characteristics of nodes
Required node	1-10	Responsible for the ship's power system and other fundamental system operation tasks, in three combat environments have a high degree of importance.
Combat node	11-35	Responsible for the detection and interception missions of the system, with different importance levels in the three operational environments according to the operational capabilities.
Optional node	36-50	Responsible for unimportant tasks, low priority in wartime maintenance, low importance in all three operational environments.

Combat node refers to the equipment node that can detect and intercept enemy attack. Its detection probability (or interception probability) is given separately. The information of some operational nodes is shown in Table 2.

In order to better describe the damage and repair of system nodes in wartime, the effectiveness grade matrix E of system nodes is introduced. The equipment node has 6 efficiency states respectively, which are represented by 0-5 from low to high. Level 5 is the highest, indicating that the node is intact and has 100% combat capability to resist attacks. Level 0 is the lowest, indicating that the node is damaged and the node efficiency is 0%, that is, the node is completely unable to complete the interception task. After the ship is attacked, the effectiveness level of equipment is reduced according to the degree of damage, and after certain maintenance, the effectiveness level of nodes is restored to a certain value or even completely restored to the highest. Levels 4, 3, 2 and 1 respectively indicate that the node has basically no damage, slight damage, moderate damage and severe damage, and the node efficiency is 80%, 60%, 40% and 20% of the intact state. The efficiency grade matrix represents the current efficiency grade of the 50 nodes, and the initial value is 5. If the nodes are damaged, the new efficiency grade matrix is equal to the original efficiency grade matrix minus the damage matrix.

Table 2. Information of some combat nodes.

Number of node	Name of node	Tasks of nodes	Node capability
11	The radar detection	Detection of high-altitude aircraft/missiles and low-altitude drones	0.85
16	The sonar detection	Detection of underwater torpedoes	0.55
21	Long-range anti-aircraft missile	Intercept high-altitude aircraft missiles	0.80
26	Anti-aircraft artillery	Intercept low-altitude drones	0.85
31	Anti-submarine missile	Interception of underwater torpedo	0.60

3.3 Explosion Damage Model

After the ship is attacked by the enemy, the system node damage matrix $E_{Destroy}$ is introduced to describe the damage degree of the node. At the beginning of each attack, the attack and defence situation of the current wave is determined first. Then, based on the shockwave overpressure formula[12], damage degree of each node of the defence system is determined according to the W_{TNT} (TNT equivalent) of the successful enemy attack and the landing point, and the damage matrix is accumulated. The damage degree of the system node is not only related to the W_{TNT} and center position of the explosion source, but also to the current efficiency level of the combat node. Therefore, the damage degree of equipment is a multivariate function of damage radius and current damage recovery degree. Shock wave overpressure ΔP is in equation (5):

$$\Delta P = 1.1\frac{1}{R'} + 4.3\frac{1}{R'^2} + 14\frac{1}{R'^3} \tag{5}$$

$$R' = \frac{R}{\sqrt[3]{W_{TNT}}} \tag{6}$$

where R' is the equivalent distance, R is the distance between the equipment node and the explosion center. In order to describe the influence of multi-wave attack on the effectiveness level, the mathematical model of the current effectiveness level is as follows, which is the difference between the effectiveness level matrix of the previous state and the current damage matrix:

$$E^{n+1} = E^n - E_{Destroy} \tag{7}$$

4. RECOVERY STRATEGY AND ALGORITHM PRINCIPLE

This paper deals with the optimal maintenance strategy of ships facing multi-wave attack under emergency wartime. In view of different battlefield environments, Attack Defence Recovery Strategy (ADRS) is proposed. Specifically, in single-wave maintenance, the wartime importance of equipment nodes is determined according to the types of enemy attacks, that is, the importance of different types of nodes to deal with different attacks is determined. So the maintenance sequence output by the algorithm is more inclined to the equipment node that can resist the next wave attack. The general recovery strategy refers to that in non-combat state, the system equipment nodes are repaired according to fixed importance without distinguishing node types and node tasks. Compared with the general recovery strategy, ADRS can improve the adaptive ability of combat system in wartime more effectively.

In this study, the multi-group parallel maintenance sequence problem with multiple constraints in a limited time is modelled. The parallel maintenance of M maintenance teams corresponds to the departure of M traveling salesmen to visit different cities. Constraints can be divided into time constraints, maintenance spare parts constraints, and maintenance personnel constraints. The mathematical model of maintenance strategy can be described as follows: It is known that n nodes need to be repaired after the system is disturbed, and different node equipment needs several parts of A, B and C. There are S group of maintenance personnel to complete the repair task together, each group carries a number of A, B, C parts from different damaged nodes, that is, the output degree of each node is 1. Repair and restore different damaged nodes within a limited time, and each node is repaired once, that is, the entry degree of each node is also 1. The objective of the model is to find a maintenance path with the highest node importance that can be repaired by the maintenance personnel of S group within limited time and limited spare parts, as shown in equations (8) and (9).

$$total\ degree = \sum_{i=1}^{S} degree_i \tag{8}$$

$$degree_i = \sum_{k=1}^{n} Z[p(k)] \tag{9}$$

where, $total\ degree$ represents the wartime importance of the total nodes repaired by all maintenance teams. S represents the number of maintenance teams, $degree_i$ represents the wartime importance of the total nodes corresponding to the maintenance sub-path of maintenance team *I*, *N* represents the index of the last node repaired by the corresponding maintenance team, and $Z[p(k)]$ represents the wartime importance of nodes k under the current operational state.

In order to better describe the maintenance cost of nodes, the maintenance time matrix of each node is introduced. The maintenance time is determined by multiplying the number of required spare parts by the current efficiency level of equipment node after being weighted, as shown in equation (10).

$$t_k = \left(5 - E(k)\right) \cdot (5 \cdot D_{kA} + 10 \cdot D_{kB} + 15 \cdot D_{kC}) \tag{10}$$

The right side of the equation is divided into two parts. The first part represents the current missing efficiency level of node k, and the second part represents the time needed to restore an efficiency level. Where, D_{k*} represents the number of * kinds of parts required by node *K* to restore a performance level.

In this study, the genetic algorithm was used to solve the path planning of system resilience recovery. The decimal code was used to represent the node number, and the multi-chromosome code was used to represent the repair sequence of multiple groups of maintenance personnel. The optimal repair sequence was output after multiple iterations through selection, crossover and mutation operations. Individual codes are shown below：

$$popRoute = [3, 4, 1, 43, 13, 16, 35, 28, 30, 11, 12, 9, 49, 2, 5, 23, 29]$$

$popBreak = [5, 11, 14]$

where $popRoute$ refers to the decimal coding individual, $popBreak$ refers to the corresponding breakpoint of the individual to form the polysomal coding. Three breakpoints indicate that there are four groups of maintenance personnel to complete the maintenance task, and the maintenance nodes of each group are expressed as follows: [3, 4, 1, 43], [13, 16, 35, 28, 30, 11], [12, 9, 49], [2, 5, 23, 29].

At the end of each wave of attack, the wartime importance value of nodes corresponding to the battlefield environment is provided for the genetic algorithm, so that the genetic algorithm tends to get the population fitness value which is more favourable to the next wave of confrontation task during calculation. The length of gene sequence adaptively is adjusted according to the number of nodes to be repaired, the maintenance sequence with the highest overall task importance of all maintenance teams within limited time and spare parts is obtained, and the recovery matrix $E_{Recovery}$ of current wave times is recorded. And the recovery matrix and the current efficiency grade matrix E^n are added to obtain the new efficiency grade matrix E^{n+1}, which is expressed as equation (11).

$$E^{n+1} = E^n + E_{Recovery} \tag{11}$$

5. SYSTEM SIMULATION AND ANALYSIS

In this study, the resilience of the system is discussed from the recovery ability of the system under the attack of multiple enemy waves by using the quotient resilience model. The expression of system resilience *R* is shown in equation (12).

$$R = Recovery/Loss \tag{12}$$

$$Recovery = \sum_{i=1}^{n} Recovery_i \tag{13}$$

$$Loss = \sum_{i=1}^{n} Lossi_i \tag{14}$$

where, *n* is the wave number of enemy attack, Recovery and Loss are respectively the sum of the Recovery matrix and damage matrix in all wave times. In order to facilitate the comparative experiment, only the importance matrix of equipment node used in the operation of the algorithm was changed to fix the detection/interception probability of combat equipment node and the attack probability of enemy attack, and the advantages of ADRS compared with general recovery and recovery strategies in different combat environments were analysed.

(1) Multi-wave UAV attacks

UAV attacks represent attacks with low damage and easy interception. The serial number of the combat node in the current combat scenario is [11, 12, 13, 14, 15, 26, 27, 28, 29, 30]. When all attacks are drones, the maintenance recovery of each wave is as follows:

After the first attack, the system recovery nodes based on the general recovery strategy are [[22, 27, 36, 49, 46, 26], [38, 6, 8, 14, 7, 1, 50], [12, 15, 42, 47, 5], [23, 41, 28, 11, 44, 48, 25], [40, 16, 10, 43, 9, 45, 37, 39]], there are seven combat nodes. The system recovery nodes based on ADRS are [[3, 8, 6, 18, 4, 1, 49], [15, 22, 27, 26, 25, 29], [24, 11, 36, 14, 28, 7, 43], [37, 50, 12, 30, 5, 48, 38], [40, 21, 42, 41, 10, 13, 9, 2]], there are eight combat nodes.

After the second attack, the system recovery nodes based on the general recovery strategy are [[10, 16, 43, 37, 4, 7, 47, 9], [39, 40, 20, 13, 50, 17, 42, 25], [22, 27, 23, 26, 49, 14, 28], [6, 41, 3, 18, 12, 1, 2], [8, 24, 32, 46, 45, 38, 36, 48]], there are five combat nodes. The system recovery nodes based on ADRS are [[12, 42, 37, 20, 39, 16], [46, 48, 14, 29, 26, 45, 24, 28, 1], [38, 7, 17, 13, 27, 21, 3, 31], [8, 10, 19, 6, 4, 25, 2], [11, 47, 50, 34, 15, 30, 9]], there are eight combat nodes.

The process of the system resilience recovery is shown in Figure 1. Because of the small damage and low interception difficulty, there is no pressure on the maintenance of the system and it can be fully repaired under multiple constraints. The system resilience R is 1, but it can be seen that after the first wave of maintenance, the damage suffered by the second wave is reduced, which can keep the system at a high efficiency level. Therefore, it can be seen that ADRS is slightly better than the general recovery strategy.

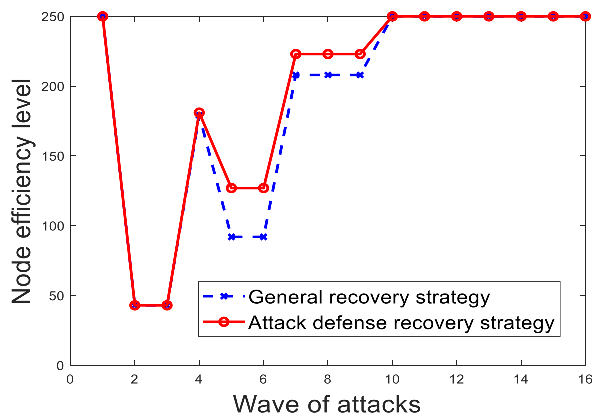

Figure 1. System resilience under multi-wave UAV attack.

(2) Multi-wave aircraft/missile attacks

Aircraft/missile represents the enemy attack mode with moderate damage and interception difficulty. The serial number of the combat node in the current combat scenario is [11, 12, 13, 14, 15, 21, 22, 23, 24, 25]. When all attacks are aircraft/missile, the maintenance recovery of each wave is as follows:

After the first attack, the system recovery nodes based on the general recovery strategy are [[26, 27, 24, 44, 2, 1], [37, 50, 12, 16, 9, 45, 48], [39, 40, 10, 5, 4, 42, 49], [43, 6, 8, 41, 7], [3, 38, 14, 47, 36]], there are two combat nodes. The system recovery nodes based on ADRS are [[14, 11, 3, 7], [37, 42, 10, 8, 6 ,2, 4], [30, 12, 13, 41, 23, 9, 49], [24, 38, 22, 36, 1, 45], [21, 18, 5, 15, 44, 25]], all operational nodes were repaired successfully.

After the second attack, the system recovery nodes based on the general recovery strategy are [[34, 18, 48, 13, 28, 4, 36], [10, 37, 40, 23, 25, 12, 9, 38], [14, 46, 44, 47, 45, 7], [39, 8, 41, 42, 50, 5, 2], [43, 22, 3, 6, 1, 49]], there are four combat nodes. The system recovery nodes based on ADRS are [[3, 27, 15, 29, 6], [50, 7, 39, 47, 4, 5, 10], [46, 24, 32, 35, 48, 12, 14], [8, 22, 21, 31, 28, 1, 2, 26], [13, 16, 9, 19, 49, 25, 45, 43, 40, 30]], there are eight combat nodes.

The process of the system resilience recovery is shown in Figure 2. Because the damage and interception difficulty are not very high, the system can gradually recover in the subsequent waves. The system resilience R is 1, but it can be seen that after the first wave of maintenance, the damage suffered by the second wave is significantly reduced, which can keep the system at a higher efficiency level. Therefore, it can be seen that ADRS is slightly better than the general recovery strategy.

(3) Multi-wave torpedo attacks

Torpedoes represent high damage and difficult to intercept attacks. The serial number of the combat node in the current combat scenario is [16, 17, 18, 19, 20, 31, 32, 33, 34, 35]. When all 5 waves are underwater torpedo attacks, the maintenance recovery of each wave is as follows:

After the first attack, the system recovery nodes based on the general recovery strategy are [[43, 5, 14, 50, 40, 1], [38, 48, 47, 22, 25, 4], [39, 20, 10, 45, 44, 2], [16, 8, 42, 12, 41, 28], [46, 23, 3, 6, 49]], there are one combat nodes. The system recovery nodes based on ADRS are [[10, 39, 41, 20, 2, 37], [35, 32, 34, 16, 4], [45, 19, 8, 9, 42, 48, 49], [18, 36, 33, 6, 1, 5], [3, 17, 38, 31]], there are nine combat nodes.

After the second attack, the system recovery nodes based on the general recovery strategy are [[40, 23, 10, 39, 28, 49, 36], [9, 12, 16, 38, 42, 48, 6], [41, 4, 8, 46, 22], [14, 44, 47, 7, 24], [37, 50, 43, 5, 25, 1]], there are one combat nodes. The system recovery nodes based on ADRS are [[33, 34, 3, 19], [16, 38, 9, 47, 10,1], [20, 39, 43, 31, 5, 4], [48, 6, 32, 8, 17], [44, 14, 35, 7, 18]], there are nine combat nodes.

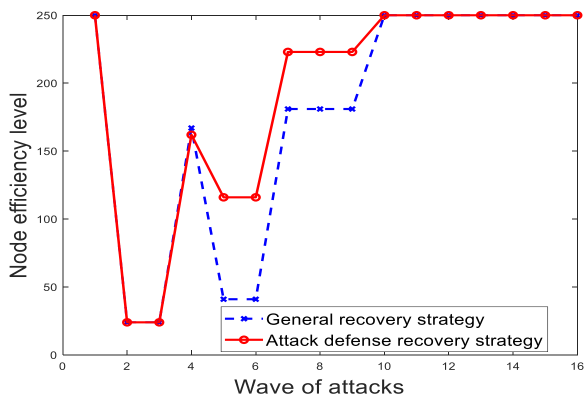

Figure 2. System resilience under multi-wave aircraft/missile attack.

The process of the system resilience recovery is shown in Figure 3. It is obvious that the attack mode of high damage can make the system suffer huge impact, and the system can only repair a certain number of nodes of efficiency level in each wave, therefore, under the general recovery strategy, although the system has repaired most nodes, it still cannot effectively avoid the next wave of attacks, and the system is still damaged. The system based on ADRS has an effective performance level in the third wave, which reduces the damage in the third wave. In the following wave, the system can successfully resist the attack and recover to the best performance state. Therefore, it can be seen that ADRS is much better than normal recovery strategy in this combat environment.

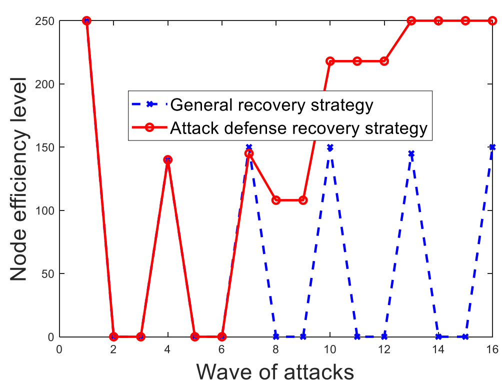

Figure 3. System resilience under multi-wave torpedo attack.

6. CONCLUSION

This paper discusses the optimization of system resilience under multi-wave attack, and analyses the system resilience from the perspective of system robustness. Firstly, from the view of damage degree and interception difficulty, the attack of different types of enemy is simulated, and the antagonistic damage model of both sides is constructed. Then, based on genetic algorithm, the length of gene sequence was adjusted flexibly under multi-wave attack, and the node repair sequence was output by cross mutation for many times. Finally, the advantages and disadvantages of ADRS in different combat environments compared with general recovery strategies are simulated and analysed. The results show that the enemy's attack damage degree and intercept difficulty can indicate the severity of the combat environment. When the combat environment is not so harsh, the damage is relatively light and the repair task is relatively easy. Although the system can be restored eventually under the two recovery strategies, the total damage of the system based on ADRS is less than that of the general recovery strategy, which can effectively improve the system resilience. In the combat environment of difficult detection and interception, and high degree of damage, the confrontation task becomes difficult and the maintenance task is difficult. Therefore, when the maintenance strategy focuses on the maintenance of combat nodes within a limited time, it can effectively resist subsequent attacks and recover the system in advance, effectively reducing the system damage. Therefore, ADRS has obvious advantages.

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