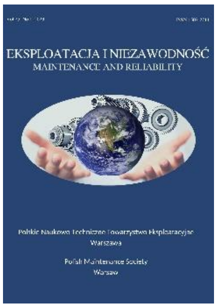

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A risk assessment method of aircraft structure damage maintenance interval considering fatigue crack growth and detection rate

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Highlights

- A new method to realize the quantitative assessment of aircraft structure maintenance intervals.
- This method considers the fatigue crack growth and crack detection rate of the structure.
- Obtained the maintenance interval with acceptable risk under the structural safety threshold.
- Realized the quantitative division of risk classification.

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Abstract

The accurate assessment of aircraft structure damage risk is the premise of establishing reasonable, economic and reliable maintenance intervals. While many studies have proposed damage risk assessment methods for aircraft structures, these methods lack the quantification of risk. This paper proposed a risk assessment method of aircraft structure damage maintenance interval considering fatigue crack growth rate and crack detection rate. The damage process of aircraft structure was simulated by Monte Carlo simulation to realize the quantitative assessment of aircraft structure damage risk and maintenance interval. Taking an aircraft fleet as an example, the damage risk of its wing structure was simulated and analyzed. The results show that if the risk is controlled within a reasonable range, the maintenance interval should be shortened to 16 flight hours. At the same time, through the analysis of the risk classification standard and the crack detection rate, the quantitative evaluation of the risk classification standard was realized.

Keywords

Monte Carlo, risk assessment, maintenance interval, crack propagation, detection rate, condition based maintenance.

1. Introduction

Aircraft maintenance is an effective measure to restore aircraft performance and reduce flight safety risks. Once the aircraft breaks down in the air, it will seriously threaten the safety of the flight safety, and even cause fatal crashes. Therefore, even if the aircraft does not fail, regular preventive maintenance should be carried out after a certain period of use to reduce the flight risk. At present, the common maintenance method for aircraft is the 'regular maintenance' strategy based on aircraft life indicators. However, in order to ensure aircraft safety, the regular maintenance interval is usually set conservatively, which causes a waste of maintenance resources. And for some aircrafts with inherent defects or high use intensity, the regular maintenance can not detect hidden risks in time. Therefore, in order to achieve aircraft reliability with higher economic effectiveness, domestic and foreign scholars have carried out a lot of research and proposed the 'condition based maintenance' method [5, 21]. At present, this maintenance method has become the key development method of aircraft maintenance. In order to realize the transformation of aircraft maintenance from 'regular maintenance' to 'condition based maintenance', the most important thing is to achieve accurate assessment of aircraft flight risk. However, there are few quantitative calculationmethods for aircraft safety indicators, and the current qualitative evaluation method is still mainly used, which makes it difficult to measure and test aircraft safety risks quantitatively. At present, the assessment methods for aircraft maintenance intervals mainly include iterative algorithm, stochastic process method, UGF method and simulation algorithm [32, 27]. The risk assessment of aircraft structure damage maintenance interval mainly adopts the analytic hierarchy process, fuzzy assessment method, etc. [31, 28]. Chang, et al [3] analyzed

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significant human risk factors in aircraft maintenance technicians (AMTs) in the airline industry with expert scoring method, and realized the analysis and ranking of major risk factors of AMT. Kiracı, et al [18] used the new multi-criteria decision making (MCDM) methods to conduct multi-dimensional evaluation and selection of commercial aircraft alternatives. Jamali, et al[15] proposed a new methodology for prioritizing strategies using an integrated approach of fuzzy Multiple Criteria Decision Making (MCDM), and a case study in an aircraft maintenance unit showed that the 'Financial' criterion and the sub-criterion of 'Competitiveness and Improving Customer Satisfaction' were the most critical ones. However, most of these methods are based on expert scoring, which is greatly affected by the subjective factors of experts, and lacks sufficient understanding of the risk mechanism of aircraft structure damage.

The Monte Carlo simulation method is often used for the maintenance interval risk assessment of aircraft component failures[4, 13]. This method is based on aircraft component failure mechanism and component failure history data to establish aircraft component failure model, and uses computer simulation method to carry out risk assessment. It realizes failure risk assessment from component failure mechanism and maintenance strategy. Lee, et al[20] used Monte Carlo method to simulate the degradation trend of aircraft landing gear brake, and applied data driven strategy to reduce the number of inspections by 36%. Weide, et al[34] applies a genetic algorithm (GA) to generate robust aircraft heavy maintenance check schedules, and used Monte Carlo to analysis the robustness of maintenance check schedules. And the algorithm reduces the total number of overhaul inspections by 7%, while increasing the utilization rate by 4.4%. Based on Monte Carlo method, Chen, et al[6] established an aeroengine failure risk simulation model to predict and evaluate the failure risk of aeroengines in the operation phase, so as to analyze the impact of different maintenance methods and inspection intervals on failure risk factors.

However, most aircraft maintenance interval risk assessments based on Monte Carlo are aimed at aircraft component failures, and there are few reports on aircraft structure maintenance interval risk assessments. Aircraft structure damage is usually due to fatigue cracks, which is characterized by long-term, hidden, sudden, etc[7, 8]. During the simulation of aircraft component faults, there are usually only two states: normal or fault, but it is difficult to find aircraft structure damage at the initial stage of crack growth[30, 12]. In addition, the failure of aircraft components would usually directly lead to related dysfunction, which is easy to be detected in time. However, the aircraft structural damage would not lead to structural failure for a long time in the initial expansion. And because the fatigue cracks are small and often hidden in the parts that are not easy to check, the detection rate is low during each maintenance. However, once the crack expands to a certain extent, the structure would break suddenly, endangering flight safety[2, 26].

Many scholars have also carried out research on the fatigue damage risk of aircraft structures[24, 9]. Kamath, etc [16] analyzed the impact of corrosion on the fatigue life of aircraft aluminum alloy structures. The results show that if the impact of corrosion is ignored in the high stress area of the structure, it will bring risks. Even if 25% of the service life is exposed to corrosive environment, the service life of the structure will be reduced by 40-55%. Gobbato, etc [11] proposed a new comprehensive probability method to predict the remaining service life of adhesive joints of composite aircraft wing structures. Lee, etc[19] predicted the crack length distribution after maintenance by using the dynamic bayesian network (DBN) models according to the reliability of non-destructive testing (NDT) and the distribution of repair crack length. However, the existing research mainly focuses on the life prediction of structures based on materials, loads, environmental factors, etc, and lacks direct quantitative guidance for the determination of aircraft maintenance intervals. At present, for the aircraft with structural damage, the risk is usually reduced by shortening the aircraft maintenance interval. However, the reduction of maintenance interval greatly improves the workload of maintenance, and it also affects the availability of aircraft. Therefore, how to accurately assess the risk of aircraft structure damage caused by maintenance intervals is crucial for formulating a reasonable, economic and reliable maintenance interval.

Therefore, based on Monte Carlo simulation method, this paper proposed an aircraft structure damage maintenance interval risk assessment method, which introduced fatigue crack growth rate and crack detection rate into aircraft structure damage maintenance interval risk assessment. Combined with the actual damage data of the aircraft structure, the quantitative assessment of the damage risk of the aircraft structure and the reliable formulation of the maintenance interval were realized. It is of great significance to realize the transformation of aircraft structure from 'regular maintenance' to 'condition based maintenance' and improve the maintainability, reliability and economy of weapons and equipment.

2. Modeling approach

2.1. Risk factors of aircraft structure damage

The damage risk of aircraft structure is closely related to the material, load, environment and maintenance of the structure. The fatigue damage of aircraft structure can be described by the fatigue crack growth rate of the material. However, the load history and service environment of different aircraft structures are not consistent. In order to obtain an accurate failure probability of the aircraft structure, the structural failure probability distribution can be obtained by fitting the historical data of aircraft service. In addition, whether the aircraft structure damage was found in time in the daily maintenance and the preventive maintenance plan of the structure are also important factors affecting the risk of aircraft structure damage.

2.1.1. Structural failure probability distribution

In reliability theory, failure distribution probability models describing product failures mainly include normal distribution, exponential distribution, lognormal distribution and Weibull distribution [17]. The Weibull distribution is often used in the reliability study of fatigue failure of structural materials [29, 23].

Probability distribution function of Weibull distribution:

$$F(t) = 1 - e^{-\left(\frac{t-\gamma}{\eta}\right)^{\alpha}} \tag{1}$$

where $F(t)$ is the probability distribution function of aircraft structure failure; α, η, γ are respectively the shape parameter, scale parameter and position parameter of Weibull distribution.

The Weibull distribution can be transformed from position parameter γ to a new distribution [22]. In order to simplify the research method, the location parameter γ can be made equal to 0, and the three parameter Weibull distribution of equation (1) can be simplified into a two parameter Weibull distribution.

Probability distribution function of two parameter Weibull distribution:

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\alpha}} \tag{2}$$

Reliability function:

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\alpha}} \tag{3}$$

Failure function:

$$\lambda(t) = \frac{\alpha}{\eta}\left(\frac{t}{\eta}\right)^{\alpha-1} \tag{4}$$

Availability of preventive maintenance:

Availability is the ability to comprehensively reflect the reliability, maintainability and supportability of a system or component, and describe the availability of a system or component at a certain time [1, 33]. Availability can be expressed as the ratio of working time to total service time:

$$A(t) = \frac{T_U}{T_{TO}} \tag{5}$$

Where $A(t)$ is the availability function; T_U is the working time; T_{TO} is the total service time.

For systems or components subject to two parameter Weibull distribution, their working time can be expressed as:

$$T_U = \int_0^T exp\left[-\left(\frac{t}{\eta}\right)^{\alpha}\right] dt \tag{6}$$

Where T is the maintenance interval.

For aircraft, multiple preventive maintenance and possible corrective maintenance are required in its total service time, so its total service time can be expressed as:

$$T_{TO} = T + t_1 + t_2\left\{1 - exp\left[-\left(\frac{T}{\eta}\right)^{\alpha}\right]\right\} \tag{7}$$

Where t_1 is the preventive maintenance time; t_2 is the time for corrective maintenance.

According to Formula (5)~(7), the availability of preventive maintenance is:

$$A(t) = \frac{\int_0^T exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] dt}{T + t_1 + t_2\left\{1 - exp\left[-\left(\frac{T}{\eta}\right)^{\beta}\right]\right\}} \tag{8}$$

2.1.2. Detection rate of structural cracks

The failure of aircraft component usually leads directly to aircraft-related dysfunction, which was easy to be detected in time. However, aircraft structural damage would not lead to structural failure for a long period of time in the initial stage of expansion. Because fatigue cracks were small and often hidden in parts that were not easy to check, the detection rate of each inspection was low [25, 35]. Therefore, this paper introduced the detection rate F_{jc} to simulate the detection probability of aircraft structural cracks during each maintenance inspection. It was supposed that the wing structure was tested once every T time. If a crack was found, the crack length was a. The number of tests it has undergone was predicted according to the crack length growth rule, the reciprocal of which was the crack detection rate F_{jc}.

$$a = f(t) \tag{9}$$

$$F_{jc} = \frac{1}{G(a)/T} \tag{10}$$

Where $f(t)$ is the fatigue crack growth equation; $G(a)$ is the inverse function of $f(t)$; T is the maintenance interval.

2.1.3. Fatigue crack growth rate

Due to the hidden characteristics of aircraft structure damage, the detection rate was low at each maintenance inspection. When a crack was found in the airframe structure, the crack length has often reached a more serious level. This means that during the period when the structural crack was not detected after it was generated, although the structure has undergone multiple maintenance inspections, the crack was still expanding gradually. Therefore, this paper introduced a fatigue crack growth equation to simulate the length of continuous crack growth during the undetected period after crack initiation. Fatigue crack growth can generally be expressed by fatigue crack growth rate and stress intensity factor amplitude, and can be described quantitatively by Paris formula [14], as shown in equation (11). According to Paris crack growth rate formula and fatigue load spectrum of aircraft structure, the relationship between fatigue crack and flight time can be obtained.

$$\frac{da}{dN} = C(\Delta K)^n \tag{11}$$

Where a is the crack growth length; N is the number of fatigue cycles; C, n are the material constant; ΔK is the stress intensity factor.

2.2. Risk assessment criteria

2.2.1. Risk severity level

The safety requirements of products are generally qualitative requirements based on the consequences of accidents caused by failures. The structural damage of aircraft is usually classified according to its damage degree and its impact on aircraft flight safety. The risk is divided into multiple levels according to the location and size of structural cracks. For example, it is divided into four levels: disaster (1), serious (2), mild (3) and minor (4). For specific systems or components, the risk rating criteria shall be jointly agreed by the user and the manufacturer. At present, there is no clear standard specification for the classification of structural crack risk, which is usually determined based on the assessment of the equipment user and the aircraft manufacturer. In this paper, the risk level of aircraft structure is determined according to the location and length of cracks. Table 1 provides a classification standard.

Table 1 Classification of risk severity levels.

Level	Severity	Grading standard a_0/mm
1	disaster	$a_0 > 50$
2	serious	$10 < a_0 \leq 50$
3	mild	$5 < a_0 \leq 10$
4	minor	$a_0 \leq 5$

2.2.2. Risk possibility level

The possibility of the risk is also an important indicator for risk assessment. According to the probability of the failure, the US military standard MIL-STD-882D divides the accident probability into five levels [10]: frequent (A), very likely (B), sometimes (C), rarely (D) and impossible (E), as shown in Tab. 2.

Table 2 Classification of risk likelihood levels.

Level	Possibility	Probability
A	frequent	$>10^{-1}$
B	very likely	10^{-1}~10^{-2}
C	sometimes	10^{-2}~10^{-3}
D	rarely	10^{-3}~10^{-6}
E	impossible	$<10^{-6}$

2.2.3. Risk assessment index

The final risk level is affected by both risk severity and risk possibility, so it is inaccurate to determine the risk level only by any one of the two indicators. Therefore, the risk assessment index was introduced, and the risk index was comprehensively determined according to the severity and possibility of the risk, as shown in Table 3. In Table 3, the lower the assessment index is, the higher the risk level is; the higher the assessment index is, the lower the risk level is. According to the assessment index, the risk is divided into four levels, as shown in Table 4.

Table 3 Risk assessment index matrix.

	Disaster (1)	Serious (2)	Mild (3)	Minor (4)
Frequent (A)	1	3	7	13
Very likely (B)	2	5	9	16
Sometimes (C)	4	6	11	18
Rarely (D)	8	10	14	19
Impossible (E)	12	15	17	20

Table 4 Risk assessment level.

Level	Assessment index	Degree of acceptance
I	1~5	unacceptable
II	6~9	the user needs to make a decision on the undesired risk
III	10~17	acceptable after the user's review
IV	18~20	acceptable without review

2.3. Risk assessment process

2.3.1. Risk assessment method of aircraft structure damage

The aircraft structure damage risk assessment is to assess the structural risk of the fleet by simulating the current structural damage of each aircraft in the fleet, so as to implement the risk assessment of the maintenance interval. The risk assessment method is as follows:

(1) The failure probability of aircraft structure was determined according to the historical damage data of the fleet structure; the risk level of aircraft structure was determined according to the position and size of structural cracks; the detection rate of structural damage was determined according to the historical damage data and maintenance history of the fleet structure; the fatigue crack growth rate of the structure was determined according to the material, structure characteristics and fatigue load spectrum of the aircraft.

(2) A Monte Carlo simulation model was established to simulate the damage of aircraft structures. Based on that, we judged whether the structural damage has been detected in previous maintenance and inspection, calculated the crack growth length, and recorded the risk level of structural cracks.

(3) According to the current use of aircrafts in the fleet, we simulated the damage of all aircrafts, and counted the risk times corresponding to the structural damage of aircrafts in the fleet. According to the number of structural damage risks of the fleet, the risk probability of the fleet under different levels of risk was calculated. The risk assessment index shall be determined according to the severity and possibility of the risk, and the final risk level shall be determined accordingly.

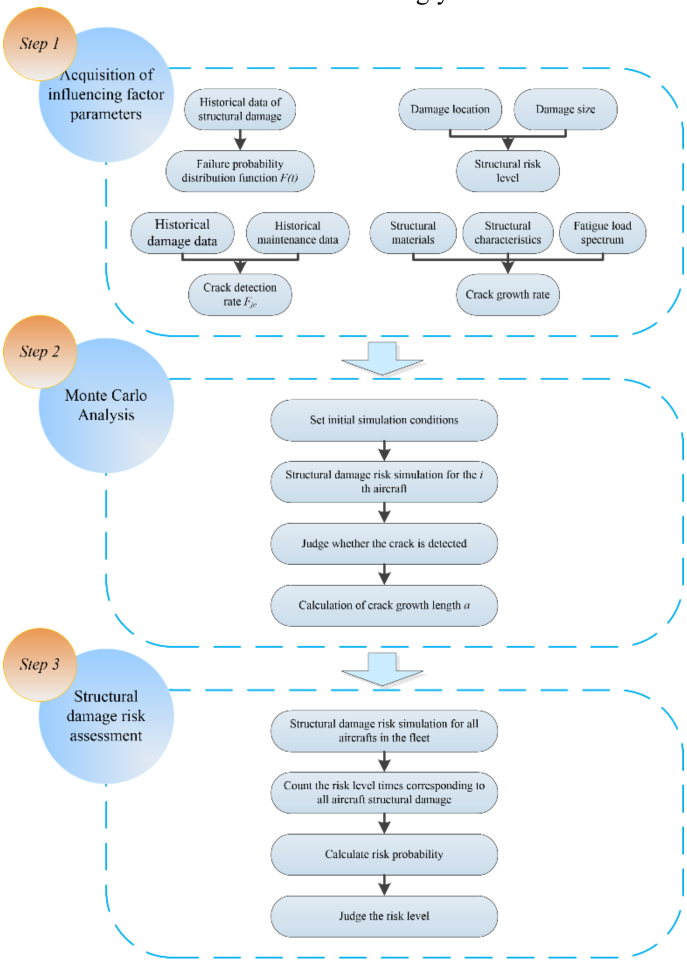


Fig.1 Risk assessment method.

2.3.2. Monte Carlo simulation process

(1) Set the initial simulation conditions: the number of the aircraft is n; the service time of the i th aircraft in the fleet is t_{si}; the aircraft structure maintenance interval is T; the probability distribution function of aircraft structure failure is $F(t)$.

(2) The structural damage risk of the i th aircraft in the fleet was simulated. Assuming that the structural failure probability distribution function $F(t)$ obeyed the uniform distribution of (0, 1), the structural failure probability of the i th aircraft was obtained by random sampling, and the structural crack initiation time t in the sampling simulation was calculated by formula (1).

(3) For the i th aircraft, if $t \le t_{si}$, it means that the aircraft structure has been damaged, but because the detection rate of structural cracks F_{jc} is low, the structural damage may not be detected. Therefore, it is necessary to judge whether the structural damage has been detected in previous maintenance and inspection, and calculate the crack growth length. If $t \ge t_{si}$, the aircraft structure is not damaged.

(4) When $t \le t_{si}$, calculate the number of crack inspections k from the initiation time t of structural cracks to the service time t_{si} of aircraft.

$$k = floor\left(\frac{t_{si}}{T}\right) - floor\left(\frac{t}{T}\right) \tag{12}$$

where *floor* is a function of rounding to negative infinity.

Determine whether the structural crack was found in the k maintenance inspections: if the crack was found in the k' ($k' \leq k$) inspection, the crack growth length a of the crack in the k'-time inspection is calculated according to the fatigue crack growth equation; if the structural crack was not found in the k-time inspection, the crack growth length a of the crack at the service time t_{si} was calculated according to the fatigue crack growth equation.

(5) Repeat steps (2) to (4), conduct sampling simulation for many times, and calculate the number of severity risk levels N_{jc1}, N_{jc2}, N_{jc3}, N_{jc4}, N_{wjc1}, N_{wjc2}, N_{wjc3} and N_{wjc4} of cracks according to the structural damage severity risk level. N_{jc1}, N_{jc2}, N_{jc3} and N_{jc4} represented the number of times of risk severity from level 1 to 4 corresponding to detected cracks, respectively; N_{wjc1}, N_{wjc2}, N_{wjc3} and N_{wjc4} represented the number of times of risk severity from level 1 to 4 corresponding to undetected cracks respectively.

(6) Step (2) to step (4) simulation were carried out for other aircrafts in the fleet; the number of severity risk levels corresponding to all aircraft structural damage in the fleet was counted, and the risk probability was calculated.

(7) The risk assessment index is determined according to the severity and possibility of the structural damage risk obtained, and the risk level is obtained accordingly.

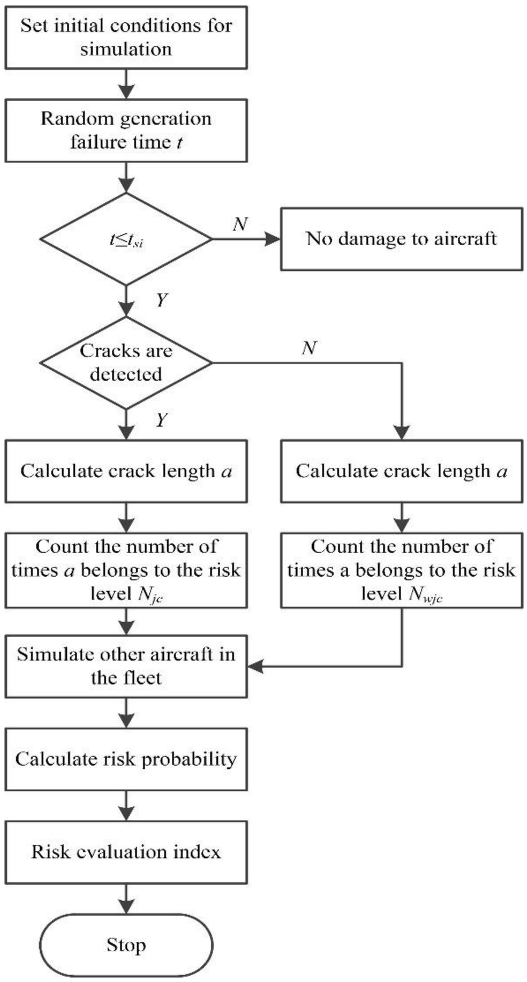


Fig. 2 Monte Carlo simulation process.

3. Case study

There are 24 aircrafts in an airport. Due to the urgent development time of this type of aircraft, the fatigue load test of airframe structure was not carried out at the initial stage of development, resulting in frequent structural damage of the aircraft fleet. In order to accurately assess the structural damage risk of the aircraft fleet and formulate a reasonable maintenance interval, this paper took the aircraft fleet as an example, carried out risk analysis combined with the historical structural damage data, and verified the risk assessment method of aircraft structural damage maintenance interval proposed in this paper.

3.1. Parameter acquisition of structural damage risk influencing factors

3.1.1. Structural failure probability distribution

According to the structural crack records of the fleet in recent years, it was found that the structural cracks of the fleet were mainly concentrated on the wing structure, so the wing structure was selected as the risk assessment object of this paper. According to the historical data of wing structure damage of the fleet in recent years, the parameters such as crack length and flight hours were selected, and the two parameter Weibull failure probability distribution parameters of the fleet structure were obtained by combining equation (2): α=2.629, η=654。

The structural damage data and fitting results are shown in Fig.3. It can be seen from the figure that the historical data of structural cracks are in good agreement with Weibull distribution function, indicating that Weibull distribution can accurately describe the probability distribution law of aircraft structural crack damage. The failure rate function of structural damage is shown in Fig.4. It can be seen from the figure that the wing structure failure rate of this fleet is relatively high, indicating that its mean time between failures (MTBF) is relatively short, and more frequent preventive maintenance work would be required with the increase of flight hours.

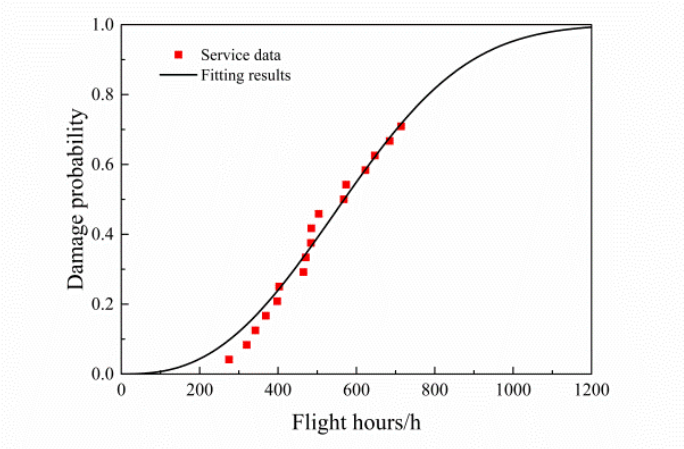


Fig.3 Weibull distribution of structural damage.

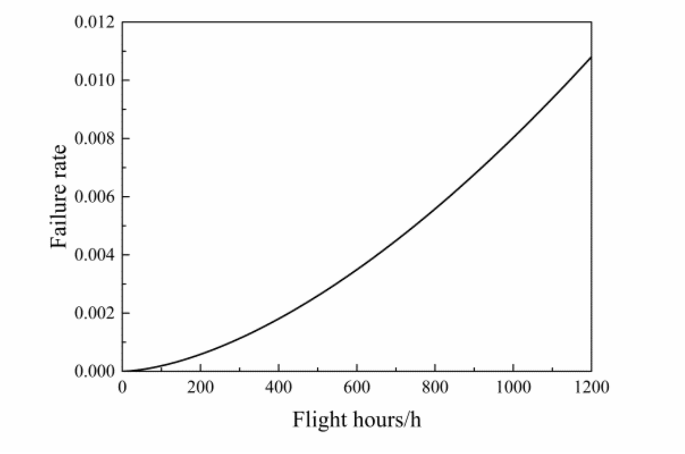


Fig.4 Failure rate function.

The relationship between the wing structure availability and the preventive maintenance interval of the fleet was calculated and analyzed by using the preventive maintenance availability model in Equation (5). Preventive maintenance time t_1 and corrective maintenance time t_2 are closely related to the maintenance ability of the maintenance unit. Different maintenance units and the proficiency of maintenance personnel will affect t_1 and t_2. In order to analyze the relationship between the unavailability of aircraft structure damage and the preventive maintenance interval, this study took five groups of t_1 and t_2 values respectively, and calculated the relationship between the unavailability and the preventive maintenance interval, as shown in Fig.5.

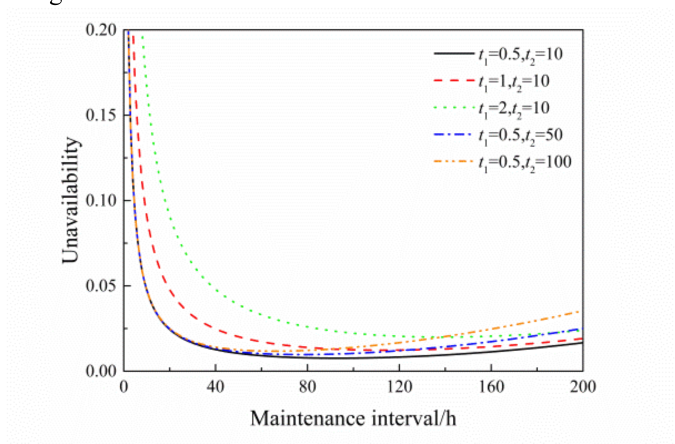


Fig.5 Relationship between unavailability and preventive maintenance interval.

It can be seen in Fig.5 that the preventive maintenance interval is related to the preventive maintenance time t1 and the fault repair maintenance time t2. The maintenance intervals corresponding to the maximum availability of five different maintenance capabilities are shown in Table 5. The greater the preventive maintenance time t1, the greater the maintenance interval; The greater the repair time t2, the smaller the repair interval.

Table 5 Maintenance interval of maximum availability corresponding to different maintenance capabilities.

Maintenance unit	t_1	t_2	Maintenance interval/h
1	0.5	10	93
2	1	10	115
3	2	10	138
4	0.5	50	77
5	0.5	100	66

It can be seen in Fig.5 that the preventive maintenance interval is related to the preventive maintenance time t_1 and the fault repair maintenance time t_2. The maintenance intervals corresponding to the maximum availability of five different maintenance capabilities are shown in Table 5. The greater the preventive maintenance time t_1, the greater the maintenance interval; The greater the repair time t_2, the smaller the repair interval.

3.1.2. Detection rate of wing structure cracks

The distribution of cracks on the wings of this fleet was relatively concealed. When the cracks were first found, the crack propagation length was long, so it was often difficult to detect during maintenance inspections, resulting in a low detection rate. For this reason, the crack detection rate F_{jc} was introduced to simulate the probability of finding cracks in the aircraft structure during each maintenance inspection. According to the distribution position of cracks in the wing structure of the fleet and the size when cracks were first found, the crack detection rate F_{jc}=0.1 was calculated from equation (10).

3.1.3. Fatigue crack growth equation

The fatigue crack growth equation of the structure was determined based on the fatigue test of the wing structure materials. The fatigue load spectrum was obtained according to the statistics, sorting and analysis of the flight training program. The load spectrum was modified considering the large and medium overload mission frequency of the aircraft model, and the relationship between the peak and valley values of the load spectrum and the flight time was obtained. Then the *a*-*t* equation of fatigue crack growth could be obtained from the crack detection data of the wing structure of the fleet.

$$a = 2.818 \times 10^{-6} t^{2.565} - 2.818 \times 10^{-6} \tag{13}$$

3.2. Risk analysis of maintenance interval

The initial service time of 24 aircrafts of the fleet was substituted into the simulation model. By setting different maintenance intervals *T*, the above parameters and risk assessment process were used to simulate the structural risk of the fleet. Under different maintenance intervals *T*, each aircraft was simulated 100 thousand times, and the fleet was simulated 2.4 million times.

3.2.1. Structural damage reliability

The probability distribution of structural crack length obtained from the simulation of the fleet is shown in Fig.6. If the acceptable value of structural crack length is set as 5 mm, which is $R_i=P\{0\leq a\leq 5\}$, the reliability distribution under different maintenance intervals *T* could be obtained as shown in Fig.7.

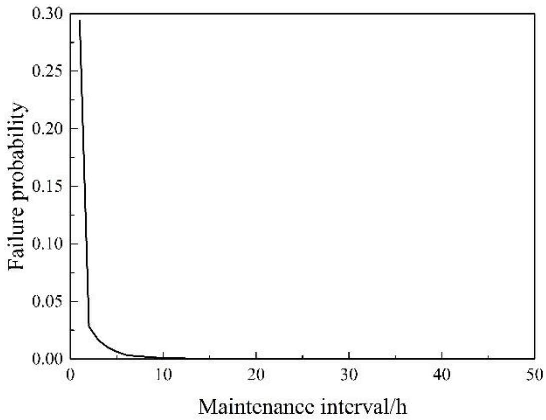
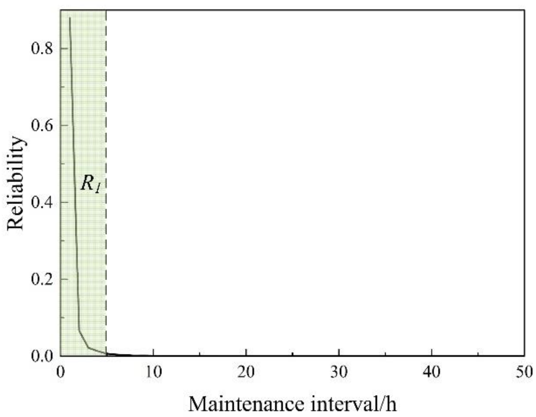
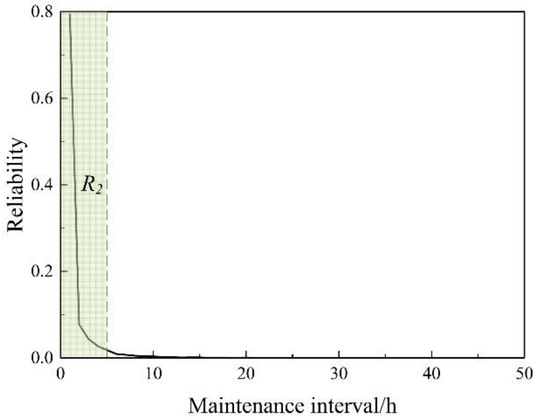


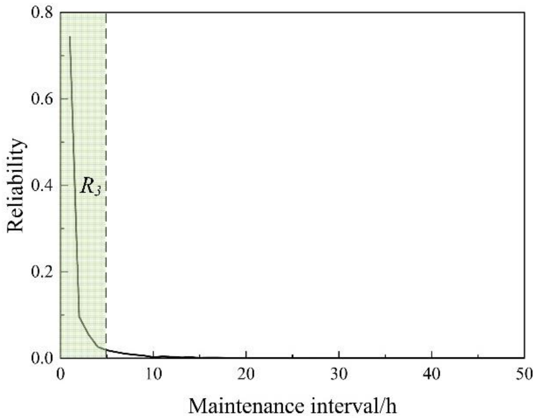
Fig. 6 Probability distribution of structural crack length (T=16 h).



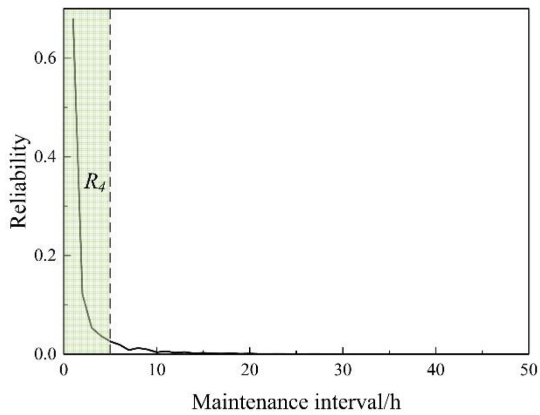
(a) T=10 h



(b)T=16 h



(c) T=20 h



(d) T=26 h

Fig.7 Reliability distribution of structural crack length.

Different risk safety thresholds were selected to calculate the structural damage risk reliability under different maintenance intervals, as shown in Table 6. Table 6 shows that the crack risk reliability of aircraft structure increases with the rise of crack safety threshold under the same maintenance interval; at the same safety threshold, the reliability of aircraft structure crack risk decreases with the increase of maintenance interval. If the risk reliability of aircraft structure cracks is expected to remain above 95%, the safety threshold and maintenance interval should be selected from the green part of Table 6.

Table 6 Structural damage risk reliability under different safety thresholds.

Maintenance interval/h	3 mm	4 mm	5 mm	6 mm
10	96.71	97.99	98.61	99.03
16	91.48	94.33	96.11	97.00
20	89.59	92.12	93.99	95.39
26	84.88	88.81	91.55	93.50

3.2.2. Structural damage risk assessment

Using the risk assessment criteria in Section 2, the risk rating of the aircraft structure crack simulation results was conducted, as shown in Table 7.

Table 7 Risk rating under different maintenance intervals.

Maintenance interval T/h		Disaster (1)	Serious (2)	Mild (3)	Minor (4)	Final risk index
10	Probability/%	0	7.90×10^{-3}	0.48	36.77	—
	Risk index	—	10	11	13	10
16	Probability/%	0	0.06	1.39	35.59	—
	Risk index	—	9	9	13	9
20	Probability/%	0	0.09	2.21	34.70	—
	Risk index	—	6	9	13	6
26	Probability/%	7.08×10^{-5}	1.13	5.30	27.22	—
	Risk index	8	5	9	13	5

It can be seen in Table 7 that the probability of minor (4) risks increases with the decrease of maintenance interval T, but disaster (1) risks, serious (2) risks and mild (3) risks decline with the decrease of maintenance interval T. And the probability of level 1 to 3 risks drop significantly, indicating that the reduction of maintenance interval can significantly reduce the high-level risk of aircraft structure damage.

When the maintenance interval T is less than 16 h, the risk assessment index is greater than or equal to 10, which is the level

Ⅲ risk. In this case, the damage risk of the aircraft wing structure needs to be reviewd by the user before acceptance. When the maintenance interval T is less than 26 h, the risk assessment index is greater than or equal to 6, which is the level Ⅱ risk. In this situation, there is an unexpected risk of wing structure damage, which needs to be decided by the user. When the maintenance interval T is greater than 26 h, the risk assessment index is less than or equal to 5, which is the level Ⅰ risk. Under these circumstances, the risk of aircraft wing structure damage is unacceptable. Therefore, according to the risk assessment criteria in this paper, the maintenance interval with appropriate risk can be formulated in combination with the user's risk acceptability.

Obviously, if the user can only accept the risk below Level Ⅲ, the maintenance interval of the wing structure of this type of aircraft would be shortened to 16 hours, but the maintenance interval of 16 hours will bring heavy burden to the aircraft maintenance work. The analysis shows that the reason for the short maintenance interval is mainly because the design task profile of this type of aircraft does not conform to the actual use profile, and the long-term use of the aircraft beyond the design standard has caused serious damage to the wing structure. Therefore, in addition to strengthening the maintenance of wing structures, other effective measures should be taken to control the risk, such as limiting the use of this type of aircraft according to design standards and strengthening the wing structures.

3.2.3. Structural damage risk probability

In addition, for the safety requirements of the aircraft structures, it is sometimes required to give the risk probability index per flight hour. According to the average service time t_m of 24 aircrafts in the fleet, the risk probability of structural damage of the fleet per flight hour can be calculated from equation (14). The calculated risk probability of aircraft structural damage under different maintenance intervals T is shown in Fig.8.

$$F_d = \frac{N_d}{t_m N} \tag{14}$$

Where F_d is the risk probability per flight hour of the fleet; N_d is the number of aircraft structure damage obtained by simulation; t_m is the average service time of all aircrafts in the fleet; N is the total number of simulations.

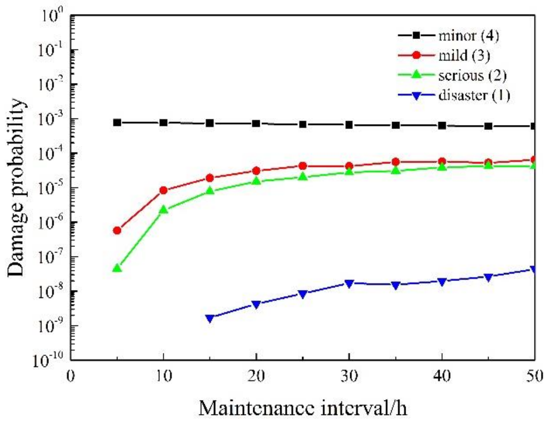


Fig.8 Risk probability of aircraft structure damage under different maintenance intervals.

Fig.8 shows that when the maintenance interval is within the range of 10-50 h, the probability of minor (4) risks per flight hour is less than 10^{-3}; the probability of minor (3) and severe (2) risks is less than 10^{-4}, and the probability of disaster (1) risks is less than 10^{-7}. It is generally believed that when the probability of flight risk is lower than 1×10^{-7}, the risk of catastrophic accident is acceptable. Therefore, when the maintenance interval is less than 50 h, the risk of catastrophic accident of wing structure damage of the fleet can be accepted.

3.3. Impact of risk classification standards on maintenance intervals

Different risk classification standards for aircraft structures would have a significant impact on the risk assessment results. A reasonable classification standard could accurately describe the risk level faced by aircraft structures and provide support for maintenance decisions. However, in many cases, the classification of risk levels is still determined qualitatively based on experience, so it is an urgent problem to determine the risk classification standard by quantitative methods. Based on the risk assessment method proposed in this paper, the impact of the risk rating standard on the maintenance interval was discussed and analyzed, in order to propose a quantitative determination method of the risk rating standard.

Taking the risk severity level as an example, the simulation was carried out for different risk severity level classification standards, and the impact of different risk severity level classification standards on maintenance intervals was analyzed. The maintenance intervals corresponding to risks at each level under different standards are shown in Fig.9-11.

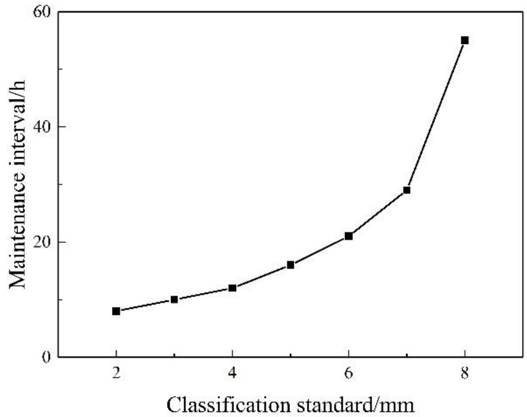


Fig.9 Impact of minor (4) risk classification standard on maintenance interval.

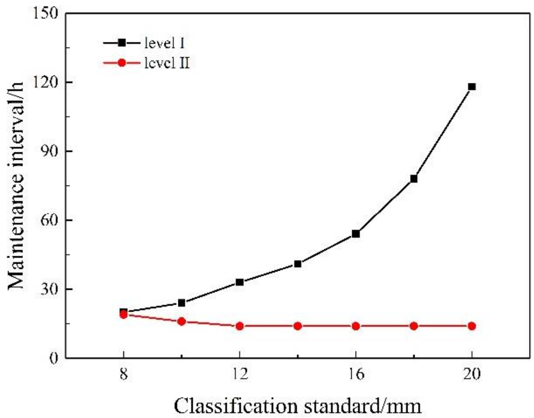


Fig.10 Impact of mild (3) risk classification standard on maintenance interval.

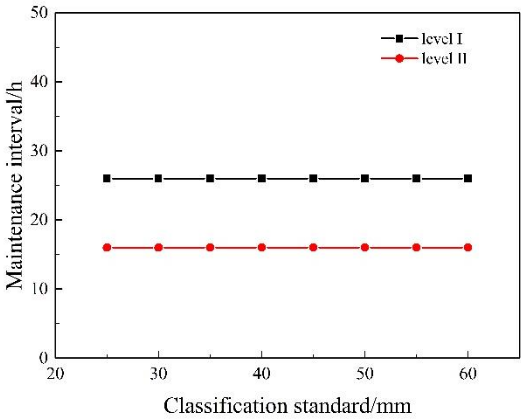


Fig.11 Impact of severity (2) risk classification standard on maintenance interval.

It can be seen in Fig.9 that with the increase of the standard of minor (4) risk, the maintenance interval corresponding to the level Ⅱ risk also increases gradually. The fitting relationship between risk level standard and maintenance interval is shown in Table 8. The risk assessment index matrix in Table 3 shows that when the risk severity level is slight (4), even if the risk probability level is the highest frequent (A), the risk assessment index is 13, reaching the level Ⅲ of risk assessment. Therefore, the classification standard of the risk severity level of minor (4) is the key to balance the structural risk and maintenance cost. The minor (4) standard shall be determined according to the damage tolerance design of aircraft structure and the comprehensive assessment of actual use, so as to ensure that the set classification standard would neither make the structural damage with higher risk be wrongly classified as an acceptable low risk, nor increase the maintenance cost of the aircraft significantly.

It can be seen in Fig.10 that the maintenance interval corresponding to the level Ⅰ risk increases with the rise of the mild (3) risk level standard, and the maintenance interval corresponding to the level Ⅱ risk decreases with the reduction of the mild (3) risk level standard. The classification standard of risk severity level (3) determines the distribution ratio of the level Ⅰ risk and the level Ⅱ risk. Under a reasonable classification standard, the structural damage of the level Ⅰ risk and the level Ⅱ risk conform to the probability distribution of risk accidents.

It can be seen in Fig.11 that the maintenance intervals corresponding to Level I and Level II risks have no obvious relationship with the severity (2) risk level standard. Because the severity (2) risk level standard mainly affects the classification of structural damage to disaster (1) or severity (2), these two levels of damage account for a relatively small percentage in the simulation, and are almost negligible compared with mild (3) and minor (4). Therefore, there is no significant

relationship between the maintenance intervals of Level I and Level II

risks and the severity (2) risk classification standard. To sum up, the risk level can be quantitatively classified according to the simulation assessment results and the user's acceptability to the risk, and the risk level can be timely assessed and adjusted based on the actual service conditions of the aircraft and the requirements of the equipment user.

Table 8 Relationship between risk classification standard and maintenance interval.

Severity level	Risk level	Relationship	Fitting relation
Severity (2)	I	not significant	—
	II	not significant	—
Mild (3)	I	proportional	T=0.0001003×$a_0^{4.598}$+20.67
	II	inverse proportion	T=0.0006971×$a_0^{5.315}$+10.11
Minor (4)	II	proportional	T=1.104×10^5×$a_0^{-4.783}$+13.77

3.4. Impact of crack detection rate on maintenance interval

At present, the users still adopt the visual inspection as a main method for checking aircraft structure damage, supplemented by non-destructive testing (NDT). Due to the complexity of the aircraft structure, the detection rate of visual inspection is very low, and NDT can only be carried out in the repair shop, which takes a long time,and makes it difficult to conduct regular NDT. Therefore, many aircraft structural cracks have already reached a higher risk level when they were found.

The damage risk of aircraft structure under different crack detection rates was simulated, and the impact of crack detection rates on maintenance intervals was analyzed, as shown in Fig.12. It can be seen that the maintenance intervals corresponding to the level Ⅰ and level Ⅱ risks increase linearly with the crack detection rate, and the fitting relationship is: level Ⅰ risk: T=236.4×F_{jc}+1.182; level Ⅱ risk: T=154.5×F_{jc}+0.2727. It shows that with the increase of crack detection rate, the corresponding maintenance interval is also significantly extended. When the crack detection rate increases from 0.1 to 0.2, the maintenance intervals corresponding to Level I and Level II risks are extended by 2 times and 1.94 times respectively. Therefore, improving the crack detection rate is an effective means to significantly extend the maintenance interval and reduce the aircraft maintenance cost. To this end, the crack detection rate could be improved, the maintenance interval could be extended and the aircraft maintenance cost could be reduced by distributing professional testing tools, improving personnel proficiency, developing portable nondestructive testing equipment, etc.

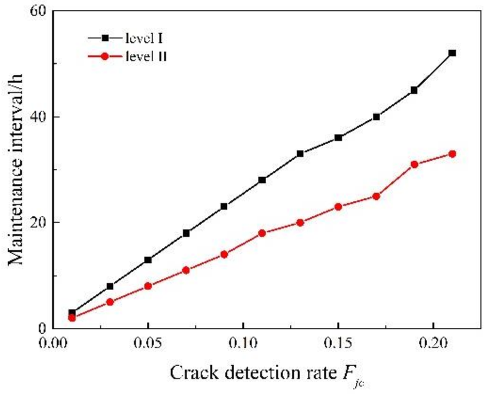


Fig.12 Impact of crack detection rate on maintenance interval.

4. Conclusion

In this paper, a risk assessment method of aircraft structure damage maintenance interval was proposed, which considered fatigue crack growth rate and crack detection rate. The damage process of aircraft structure was simulated by Monte Carlo simulation to realize the quantitative assessment of aircraft structure damage risk and maintenance interval. Taking 24 aircrafts in an airport as an example, the wing structure damage was simulated and analyzed, and the conclusions are as follows:

(1) The risk of aircraft damage is affected by both the severity and possibility of the risk. The influence of structural safety threshold on reliability of structural damage risk was analyzed, and the maintenance interval of acceptable risk was obtained. The influence of risk severity and possibility on maintenance interval was analyzed, and the results show that if the risk of wing structure damage of this type of aircraft is controlled within a reasonable range, the maintenance interval will be shortened to 16 hours. The short maintenance interval of this type of machine is mainly due to the inconsistency between the design task profile and the actual use profile, which has been used beyond the design standard for a long time.

(2) The classification standard of risk severity was discussed, and the influence of classification standard of risk severity on maintenance interval was analyzed, and the fitting relationship between the classification standard of risk severity and the maintenance interval was obtained. Through the simulation assessment results and the user's acceptability of risks, the quantitative classification of risk levels can be achieved, and the risk classification levels can be timely assessed and adjusted according to the actual service conditions of the aircraft and the requirements of the equipment user.

(3) The influence of crack detection rate on maintenance interval was simulated and analyzed, and the fitting relationship between the crack detection rate and the maintenance interval of different risk levels was obtained. The results show that with the increase of crack detection rate, the corresponding maintenance interval is significantly extended. When the crack detection rate increases from 0.1 to 0.2, the maintenance intervals corresponding to Level I and Level II risks are extended by 2 times and 1.94 times respectively. Therefore, measures can be taken to improve the crack detection rate, extend the maintenance interval and reduce the aircraft maintenance cost.

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