

Article

A Novel Individual Aircraft Life Monitoring Method Based on Reliable Life Consumption Assessment

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Abstract: Individual life monitoring is crucial for ensuring aircraft flight safety. Conventional life-consumption-based monitoring methods ignore reliability, thus disjoining them from the aircraft's reliable life determination and extension, where high confidence and reliability are required. Therefore, this paper proposes a reliable life consumption and individual life monitoring method for aircraft structure fatigue. In the paper, the P - S - N curve, i.e., the relationship between the aircraft structure's life (N) and fatigue load (S) under a certain probability (P), is established, by which the lower confidence limit of the aircraft structure's reliable life can be evaluated under any fatigue loads. Based on that and the aircraft's monitored fatigue loads, the indexes of reliable life consumption and remaining reliable life percentages are proposed and assessed in real time for individual aircraft life monitoring and online life management. Case studies indicate that the proposed method can guarantee high confidence and reliability requirements in individual life monitoring, consistent with the aircraft's life determination and extension, which are widely accepted nowadays in engineering practice.

Keywords: aircraft; reliable life; life consumption; individual life monitoring; reliability; confidence



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1. Introduction

Structural life and reliability management are critical to ensuring the aircraft's flight safety [1,2]. In past decades, the concept of "aircraft fleet management" was widely adopted, which means that each outfield aircraft is managed with a uniform standard based on the evaluated reliable life in the aircraft's full-scale fatigue test (i.e., flight hours, flight cycles, and calendar life with a specified reliability level). Currently, many types of aircraft still use this life management style. However, an aircraft's actual service loads differ from the test or design loads, and the service loads of each aircraft are also different [3,4]. Thus, the service life of each aircraft varies. If the aircraft's load is severe, its service life will be relatively short, and fleet life management based on the above life indexes will be dangerous. In contrast, if the aircraft's load is mild, the aircraft's life potential will be underestimated, resulting in significant economic waste [5]. Therefore, to ensure flight safety and improve economic efficiency simultaneously, individual life monitoring (or individual aircraft tracking) for aging and new aircraft has attracted widespread attention from industry and academia [3,6].

The main procedure of individual aircraft life monitoring is illustrated in Figure 1, including load monitoring and handling of individual aircraft, damage definition and evaluation of individual aircraft, and life prediction and management of individual aircraft [7]. Load monitoring of aircraft structures is a prerequisite. It can be realized based on flight parameter monitoring systems and strain gauges in critical parts, incorporating techniques such as finite element analysis, multiple linear regression, and artificial neural networks [8–11]. This lays a solid foundation for individual aircraft life monitoring. After obtaining service loads, the core content for individual aircraft load monitoring is defining and evaluating aircraft damage caused by service loads [5]. Nowadays, commonly used damage indexes include FI (fatigue index), FDI (fatigue damage index), FLE (fatigue life

expended), FLEI (fatigue life expended index), and CSI (crack severity index) [3,12–16]. Essentially, they can be divided into two aspects: one defines damage through aircraft's fatigue life under different loads and conducts damage accumulation or life consumption assessment based on Miner's linear cumulative damage theory [5,17]; the other defines damage in terms of crack expansion under various loads, in which damage tolerance theory is the technical core [13,16,18]. Since the former is simple for engineering practice and widely studied (e.g., Chinese military aircraft) [12], this paper focuses on individual aircraft life monitoring based on life consumption assessment.

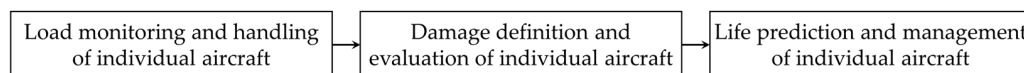


Figure 1. The main procedure for individual aircraft life monitoring.

In the aircraft's life consumption, damage per fatigue cycle is defined as the inverse of the aircraft's life N , and damage accumulation under variable loads is performed according to Miner's law [19]. For example, if an aircraft structure experiences n_i cycles under fatigue load S_i , its cumulative damage or life consumption percentage is calculated by

$$D = \sum_{i=1}^q \frac{n_i}{N_i} \quad (1)$$

where N_i is the aircraft structure's life under fatigue load S_i . The aircraft structure cannot continue being used when the damage reaches a certain threshold. Due to the dispersion of material defects, structural manufacturing, structural assembly, and others, aircraft structure life is a random variable [20]. That is, different individuals correspond to different life values, although under the same fatigue load. However, current methods generally adopt median life for the aircraft's life consumption calculation. That is,

$$D_{50} = \sum_{i=1}^q \frac{n_i}{N_{50,i}} \quad (2)$$

where $N_{50,i}$ is the median value of N_i . In fact, Equation (2) represents an average level of aircraft damage, ignoring confidence level and reliability [3]. In this case, the calculated damage D_{50} of the individual aircraft will be smaller than its actual value D with a 50% probability; that is, the actual life consumption of half of the aircraft may be underestimated. It is dangerous in engineering practice.

As a substitute for aircraft fleet management, individual aircraft monitoring is advanced because it additionally considers the specific service load of individual aircraft. However, the high reliability requirement in aircraft fleet management has been proven successful for aircraft safety [21,22], which should be inherited in individual aircraft life monitoring. As shown in Table 1, there is a lack of life-consumption-based individual aircraft life monitoring nowadays. In other words, the reliability requirement of individual aircraft monitoring is disconnected from the aircraft's life determination and extension (basic work in aircraft fleet management) conducted with high confidence and high reliability. The problem is addressed in this paper.

Table 1. Comparison of individual aircraft monitoring and aircraft fleet management.

	Individual Aircraft Monitoring	Aircraft Fleet Management
Load	Service load of individual aircraft	Typical load or load spectrum of the aircraft fleet
Reliability	Lack of consideration	High reliability (e.g., 0.999) and high confidence (e.g., 0.9)
Restrictions	Damage less than the threshold	Service time is less than the determined reliable life

To solve the above reliability contradiction and make individual aircraft monitoring more reliable and scientific, this paper proposes a reliable life consumption assessment and individual life monitoring method for aircraft structures, such as wing, fuselage, and landing gear. The main contributions are as follows:

- Based on the aircraft structure's full-scale fatigue life test, the aircraft structure's P - S - N curve, i.e., the relationship curve between the aircraft structure's life (N) and fatigue load (S) under a certain probability (P), is established. By doing so, the lower confidence limit of the aircraft structure's reliable life under any fatigue loads can be evaluated with the required confidence and reliability. This is the premise of reliable life consumption assessment.
- Based on the established P - S - N curve and the monitored service loads or flight missions of individual aircraft, the reliable life consumption percentage and remaining reliable life percentage of each aircraft can be assessed in real time. By doing so, individual aircraft life monitoring and online life management can be conveniently achieved.
- By this method, the aircraft structure's full-scale fatigue test, reliable life determination, individual life monitoring, and reliable life extension (or other life management work) can be strung together. The disconnection between individual aircraft life monitoring and reliable life determination and extension is solved.

The technology roadmap of this paper is concluded in Figure 2. Section 2 proposes a small-sample assessment method for the aircraft structure's P - S - N curve and reliable life. On this basis, Sections 3 and 4 further propose the aircraft's reliable life consumption and individual life monitoring methods, respectively. Section 5 provides an example for the method's illustration. Finally, Section 6 presents a summary of the research in this paper.

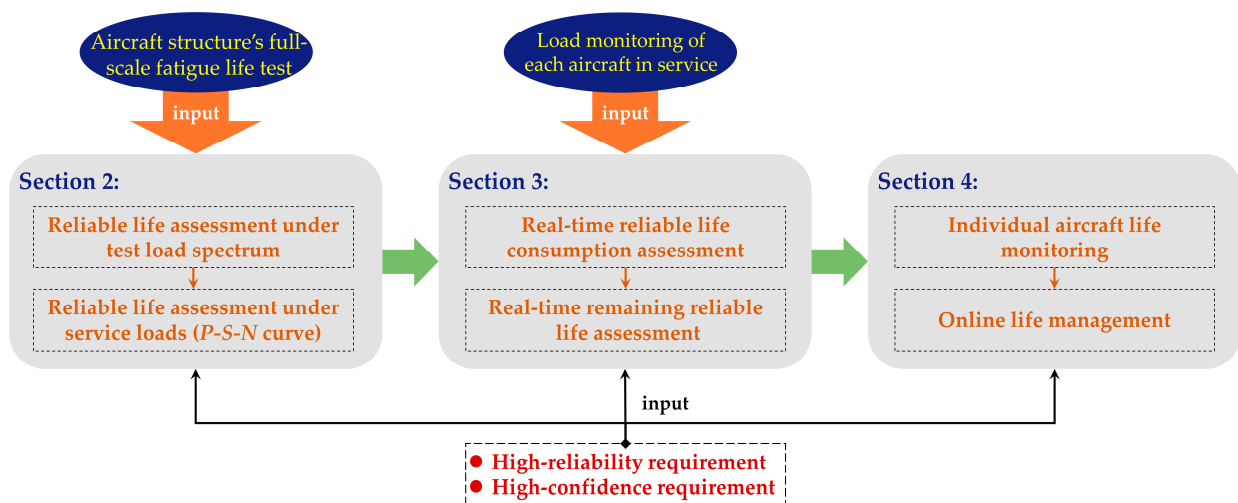


Figure 2. Technology roadmap of this paper.

2. Small-Sample Assessment Method for the Aircraft Structure's Reliable Life

Denote an aircraft structure's life as N under the fatigue load S . It is a random variable. The reliable life N_R satisfies

$$P(N \geq N_R) = R \quad (3)$$

where R is the required reliability with a common value of 0.999 [21,23].

Before the aircraft's delivery, full-scale fatigue life tests need to be conducted for reliability assessment. In this section, the aircraft structure's reliable life under different fatigue loads is evaluated based on the structure's fatigue tests. Since the true value of the reliable life N_R is not available, this section will instead target its lower confidence limit with a high-confidence requirement.

2.1. Reliable Life Assessment under Test Load Spectrum

Assume that the aircraft structure is adopted for the full-scale fatigue life test under a load block spectrum composed of load S_i^* and cycle number n_i^* , $i = 1, 2, \dots, q^*$, and the test result is $N_{B,1}^*, N_{B,2}^*, \dots, N_{B,M}^*$ (block number). According to the test result, the lower confidence limit of the aircraft structure's reliable life $N_{B,R}^*$ with confidence γ can be inferred as $N_{B,RL}^*$. For example, if the aircraft structure's life follows a lognormal distribution with a known standard deviation σ_0 (generally 0.176 or others in China [21,22]), that is

$$\lg N \sim N(\mu, \sigma_0) \quad (4)$$

then $N_{B,RL}^*$ can be estimated as

$$N_{B,RL}^* = 10^{\bar{x} - (u_R + \frac{u_\gamma}{\sqrt{M}})\sigma_0} \quad (5)$$

$$\bar{x} = \frac{1}{M} \sum_{j=1}^M \lg N_{B,j}^* \quad (6)$$

$$P(N_{B,RL}^* \leq N_{B,R}^*) = \gamma \quad (7)$$

where μ is the mean parameter; $u_R = \Phi^{-1}(R)$ and $u_\gamma = \Phi^{-1}(\gamma)$; and $\Phi(\cdot)$ is the cumulative distribution function of the standard normal distribution. If the aircraft structure's life follows a lognormal distribution with an unknown standard deviation σ , that is

$$\lg N \sim N(\mu, \sigma) \quad (8)$$

then $N_{B,RL}^*$ can be estimated by

$$N_{B,RL}^* = 10^{\bar{x} - \frac{\hat{\sigma}}{\sqrt{M}} t_{\sqrt{M}u_R, \gamma} (M-1)} \quad (9)$$

$$\hat{\sigma} = \sqrt{\frac{1}{M-1} \sum_{j=1}^M (\bar{x} - \lg N_{B,j}^*)^2} \quad (10)$$

$$P(N_{B,RL}^* \leq N_{B,R}^*) = \gamma \quad (11)$$

where $t_{\sqrt{M}u_R, \gamma} (M-1)$ is γ -quantile of the non-central t distribution with freedom degree of $\sqrt{M}u_R$.

In aircraft fleet management, the aircraft structure's reliable life is determined based on Equation (5) or (9) and full-scale fatigue tests. Then, all aircraft structures of the same type are managed by the calculation result without considering the aircraft's load difference. To further achieve individual aircraft monitoring, the premise is to establish the relationship between the aircraft structure's reliable life and fatigue load.

2.2. P-S-N Curve Determination and Reliable Life Assessment under Service Load

The aircraft structure's S - N curve describes the relationship between the life N and fatigue load S , while the P - S - N curve (probability S - N curve) is defined as the relationship between the aircraft structure's reliable life N_R (with failure probability of $1-R$) and fatigue load S . In general, the metal structure's S - N curve follows an inverse power law model [24,25], so the aircraft structure's P - S - N curve can be expressed as

$$N_R S^{m_R} = C_R \quad (12)$$

where m_R (the slope of the P - S - N curve in log-log plot) and C_R are parameters to be determined.

For aircraft structures such as wings, fuselage, and landing gear, it is generally impossible to conduct numerous full-scale fatigue tests under various load levels. Therefore, the slope parameter m_R of the P - S - N curve cannot be obtained by full-scale fatigue tests. Instead, it is generally fitted by numerous accumulated life test data of material specimens or simulation specimens in engineering practice [5]. Conventional life consumption methods assume that the slope parameter is known [6,12]. This paper also retains this assumption. Then, the determination method of C_R is explained below.

Denote the lower confidence limit of the aircraft structure's reliable life under fatigue load S_i^* as $N_{RL,i}^*$ with the confidence level of γ and reliability of R . According to the aircraft structure's P - S - N curve, it can be expressed as

$$N_{RL,i}^* = C_R (S_i^*)^{-m_R} \quad (13)$$

Then, the aircraft structure's reliable damage (defined in Section 3) caused in each test load spectrum of the full-scale fatigue life test with the confidence level of γ and reliability of R can be expressed as

$$D_{RU} = \sum_{i=1}^{q^*} \frac{n_i^*}{N_{RL,i}^*} = \sum_{i=1}^{q^*} \frac{n_i^* (S_i^*)^{m_R}}{C_R} \quad (14)$$

In addition, according to the estimated reliable life $N_{B,RL}^*$ in Section 2.1, the above reliable damage can also be calculated as

$$D_{RU} = \frac{1}{N_{B,RL}^*} \quad (15)$$

According to Equations (14) and (15), the following can be derived

$$\frac{1}{N_{B,RL}^*} = \sum_{i=1}^{q^*} \frac{n_i^* (S_i^*)^{m_R}}{C_R} \quad (16)$$

$$C_R = N_{B,RL}^* \sum_{i=1}^{q^*} n_i^* (S_i^*)^{m_R} \quad (17)$$

Then the aircraft structure's P - S - N curve with the confidence level of γ and reliability of R can be obtained as

$$N_{RL} S^{m_R} = C_R \quad (18)$$

Given any fatigue load S , the lower confidence limit of the aircraft structure's reliable life can be calculated as

$$N_{RL} = C_R S^{-m_R} \quad (19)$$

It is worth noticing that m_R is assumed to be known in this paper. When the point estimate $\hat{m}_R$ and lower confidence limit m_{RL} of m_R differ significantly in the fitting process, m_{RL} should be adopted to obtain a more conservative P - S - N curve. The specific process will not be explained here.

3. Reliable Life Consumption Assessment Method for the Aircraft Structure

Based on the aircraft structure's P - S - N curve, this section further proposes a reliable life consumption assessment method. It can evaluate the reliable life consumption percentage and remaining reliable life percentage of individual aircraft in real time with high reliability and confidence according to the monitored fatigue loads in outfield service.

3.1. Reliable Damage and Damage Threshold

Since the aircraft structure's life N under fatigue load S is a random variable and generally presents obvious dispersivity, high confidence and high reliability must be taken into consideration for safety demands. When an aircraft structure works n cycles under

the fatigue load S , the damage n/N is also a random variable. Therefore, the reliability of aircraft damage must also be considered.

Traditional methods define the aircraft's damage in terms of its median life, i.e., median damage, then

$$P\left(\frac{n}{N} \geq \frac{n}{N_{50}}\right) = 50\% \quad (20)$$

It can be found that half of the aircraft structure's actual damage n/N is higher than the median damage n/N_{50} , which is contrary to the aircraft's high-reliability requirement. In addition, if median damage is applied, as shown in Figure 3, the aircraft structure's damage threshold is a random variable and satisfies

$$P\left(\frac{N}{N_{50}} \leq 1\right) = 50\% \quad (21)$$

It means that half of the aircraft structure's actual damage threshold N/N_{50} is lower than 1. In this case, setting the threshold at 1 will be dangerous, whereas conducting research on the probability distribution of the threshold might make the issues complicated and inconvenient in engineering [26].

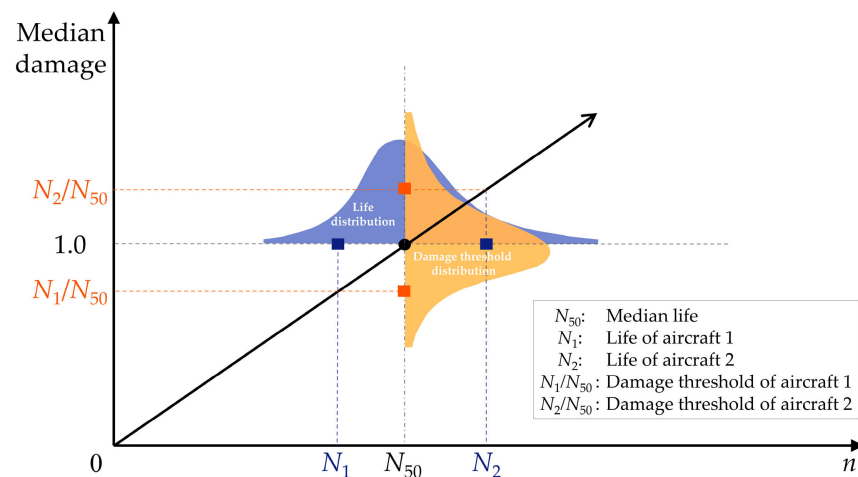


Figure 3. Schematic diagram for the threshold distribution of the median damage.

This paper defines the aircraft structure's damage in terms of its reliable life, i.e., reliable damage [27,28], then

$$P\left(\frac{n}{N} \leq \frac{n}{N_R}\right) = R \quad (22)$$

That is, it can be guaranteed that $100R\%$ of the aircraft structure's actual damage n/N is less than reliable damage n/N_R , which is safe in engineering and consistent with the concept of reliability. In addition, if reliable damage is applied, the aircraft structure's damage threshold is also a random variable, but as shown in Figure 4, it satisfies

$$P\left(\frac{N}{N_R} \geq 1\right) = R \quad (23)$$

That is, it can be ensured that $100R\%$ of the aircraft structure will not fail before the reliable damage reaches 1. Therefore, the damage threshold can be directly taken as 1. This can meet the reliability requirements and, meanwhile, facilitate engineering applications.

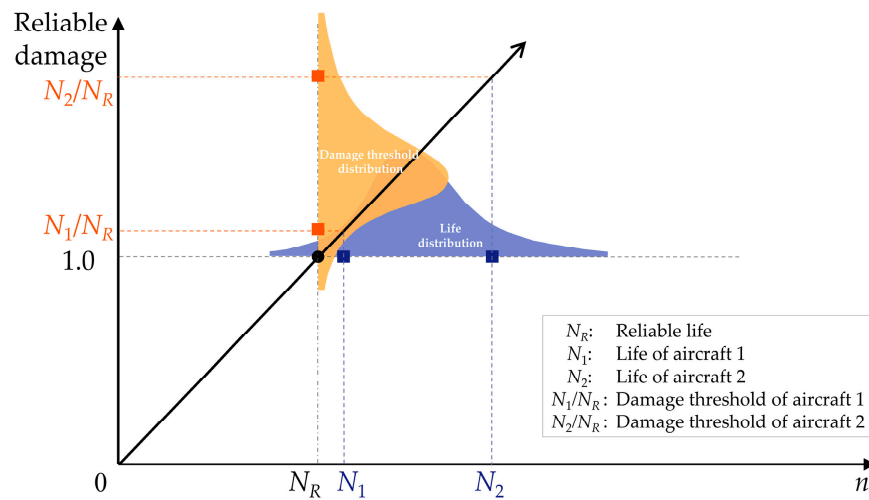


Figure 4. Schematic diagram for the threshold distribution of the reliable damage.

3.2. Reliable Life Consumption Percentage and Its Confidence Limit

Assume that an individual aircraft structure has worked for n_i cycles under fatigue load S_i at time t , $i = 1, 2, \dots, q$. Then, according to Miner's law, the aircraft structure's reliable life consumption percentage (reliable damage) with the required reliability of R is

$$L_{Ct} = \sum_{i=1}^q \frac{n_i}{N_{R,i}} \quad (24)$$

Its upper confidence limit can be evaluated by

$$L_{CUt} = \sum_{i=1}^q \frac{n_i}{N_{RL,i}} \quad (25)$$

The aircraft's remaining reliable life percentage with the required reliability of R is

$$L_{Rt} = 1 - \sum_{i=1}^q \frac{n_i}{N_{R,i}} \quad (26)$$

Its lower confidence limit can be evaluated by

$$L_{RLt} = 1 - \sum_{i=1}^q \frac{n_i}{N_{RL,i}} \quad (27)$$

where $N_{R,i}$ is the aircraft's reliable life under load S_i ; $N_{RL,i}$ is the lower confidence limit of $N_{R,i}$ with the confidence level of γ , and can be calculated through Equation (19), that is

$$N_{RL,i} = C_R S_i^{-m_R} \quad (28)$$

It can be proven that the confidence level of L_{CUt} or L_{RLt} is still γ [27], that is

$$P(L_{CUt} \geq L_{Ct}) = P(L_{RLt} \leq L_{Rt}) \geq \gamma \quad (29)$$

The indexes L_{CUt} and L_{RLt} are normalized and universal. They are applicable to all load levels and combinations, and can therefore serve well in individual aircraft life monitoring and life management. For example, if the upper confidence limit of an aircraft structure's reliable life consumption percentage is L_{CUt} , and the lower confidence limit of its remaining reliable life percentage is L_{RLt} , then the aircraft structure's equivalent

consumption fatigue cycle under load S is $L_{CUt}N_{RL}$, and the remaining reliable life under load S with the confidence level of γ and reliability of R is $L_{RLt}N_{RL}$.

4. Individual Aircraft Life Monitoring Method

Based on the reliable life consumption assessment method in Section 3 and the aircraft's load monitoring system, the aircraft's reliable life consumption percentage and remaining reliable life percentage in outfield service can be easily evaluated in real time, thus realizing individual aircraft life monitoring and online life management. In this section, load-based individual aircraft life monitoring, mission-based individual aircraft life monitoring, and online aircraft life management are introduced, respectively.

4.1. Load-Based Individual Aircraft Life Monitoring

Load-based life monitoring requires real-time fatigue load monitoring for the aircraft structure throughout the service. Much literature currently aims at fatigue load monitoring research on aircraft structures, such as [8–11]. Overall, they can be divided into two categories. One realizes structure load monitoring according to the aircraft's flight parameter system. During aircraft flight, the aircraft's flight parameters (e.g., vertical overload, mach number, height, velocity pressure, sideslip, attack angle, and others) should be recorded in real time, and the structure's fatigue load can be solved through the mapping relationship (established by multiple linear regression or artificial neural networks) between flight parameters and structural loads. Another is structure load monitoring according to strain gauges in critical parts and finite element analysis. Currently, advanced aircraft such as the F-35 generally use a mixture of the above two methods. In engineering practice, a suitable load monitoring scheme should be selected according to the aircraft's specific conditions.

The procedure for load-based individual aircraft life monitoring is illustrated in Figure 5. Assume that an individual aircraft structure has experienced n_i load cycles of S_i at time t , $i = 1, 2, \dots, q$, then the upper confidence limit of the aircraft structure's reliable life consumption percentage with the confidence level of γ and reliability of R can be calculated through Equation (25). When $L_{CUt} < 1$, the individual aircraft can still be in service, and the lower confidence limit of its remaining reliable life percentage is $L_{RLt} = 1 - L_{CUt}$.

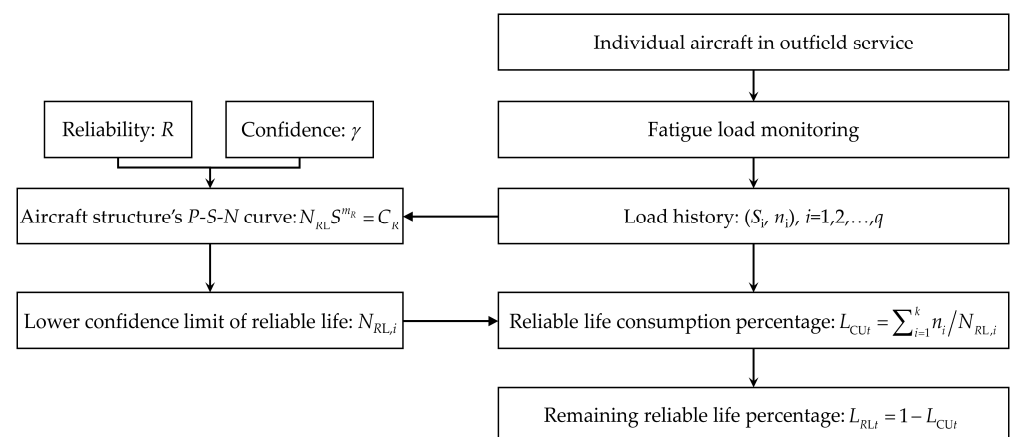


Figure 5. The procedure of load-based individual aircraft life monitoring.

4.2. Mission-Based Individual Aircraft Life Monitoring

Mission-based life monitoring requires flight mission (or flight subject) recording rather than real-time fatigue load monitoring for each aircraft, which is suitable for situations where load monitoring technology is restricted by sensing equipment. In this monitoring scheme, the aircraft structure's fatigue load history and reliable life consumption in each mission type should be estimated in advance, and then the aircraft structure's reliable life consumption in outfield service can be evaluated through the recording of

flight missions. This monitoring scheme is not high-precision because fatigue loads are not strictly the same even on the same flight mission. However, it is easy to implement, making it applicable and popular in engineering practice.

The procedure for mission-based individual aircraft life monitoring is illustrated in Figure 6. Assume that an individual aircraft structure has conducted the j_{th} mission for k_j times at time t , $j = 1, 2, \dots, K$, then the upper confidence limit of the aircraft structure's reliable life consumption percentage with the confidence level of γ and reliability of R can be calculated as

$$L_{CUt} = \sum_{j=1}^K k_j L_{CU,j} \quad (30)$$

And the lower confidence limit of the aircraft structure's remaining reliable life percentage is $L_{RLt} = 1 - L_{CUt}$. In the equation, $L_{CU,j}$ is the upper confidence limit of the aircraft structure's reliable life consumption percentage caused by each j_{th} mission, which can be calculated by Equation (25) and the fatigue load history of the mission.

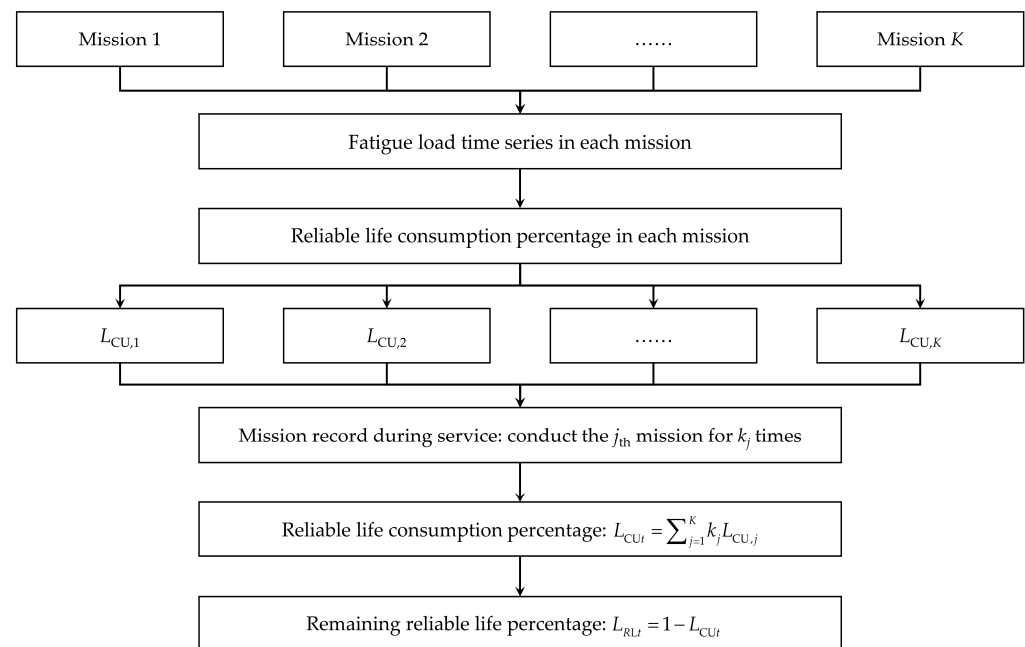


Figure 6. The procedure of mission-based individual aircraft life monitoring.

4.3. Online Aircraft Life Management

For the individual aircraft with $L_{CUt} < 1$, it can meet the required confidence level and reliability. Thus, the aircraft can still be in service with the specified reliability requirements. In contrast, for the individual aircraft with $L_{CUt} \geq 1$, it cannot meet the specified reliability requirements and cannot be allowed in service before the aircraft's life extension work. In this case, the aircraft should be scheduled for scrapping, life extension, and other management work.

For each aircraft in the fleet, the severity of flight missions and fatigue loads vary, causing the reliable life consumption to also be different. To fully exploit the service life potential of each aircraft and coordinate the aircraft fleet life to facilitate uniform management, online life management should be further conducted. For example, milder missions can be planned for aircraft with higher reliable life consumption, while severer missions can be planned for aircraft with lower reliable life consumption. Specifically, the individual aircraft with L_{CUt} and L_{RLt} can still perform the j_{th} mission alone for k'_j times, where

$$k'_j = L_{RLt} / L_{CU,j} \quad (31)$$

Furthermore, the aircraft can also be planned for mission combinations based on actual demand on the premise of

$$\sum_{j=1}^K k'_j L_{CU,j} \leq L_{RLt} \quad (32)$$

where k'_j is the number of performing times for the j_{th} mission in the mission combination scheme.

5. Example and Discussion

In this section, a military aircraft's critical structure, the central wing joint panel, is used as an example to illustrate the proposed individual life monitoring method. In the example, the aircraft's life test data is real, while the aircraft's service loads are simulated.

5.1. Reliable Life Determination under Test Load Spectrum

Five samples are adopted for fatigue life tests under the load block spectrum listed in Table 2 [29]. The test result is

$$\begin{cases} N_{B,1}^* = 20,223 \text{ (blocks)} \\ N_{B,2}^* = 16,050 \text{ (blocks)} \\ N_{B,3}^* = 22,651 \text{ (blocks)} \\ N_{B,4}^* = 20,006 \text{ (blocks)} \\ N_{B,5}^* = 15,899 \text{ (blocks)} \end{cases} \quad (33)$$

where one block means that the specimen experiences the test loads in Table 2 for one time. In the test design, the specimen is equivalent to working for one flight hour when it experiences one load block.

Table 2. Test load block spectrum of the central wing joint panel (stress ratio $r = 0$).

i	$S_i^*/(\text{MPa})$	$n_i^*/(\text{Cycles})$	i	$S_i^*/(\text{MPa})$	$n_i^*/(\text{Cycles})$
1	650	0.16	6	282	5.55
2	585	0.62	7	249	4.22
3	518	1.57	8	215	14.72
4	453	2.37	9	175	30.67
5	348	3.02	10	132	37.10

The lognormal Quantile-Quantile plot of the test result is illustrated in Figure 7. It can be found that the life of the central wing joint panel can be considered to follow a lognormal distribution. Since the dispersion parameter σ of the lognormal distribution is unknown, Equations (9)–(11) should be used for reliable life determination. Given the required reliability of $R = 0.999$ and required confidence level of $\gamma = 0.9$, the lower confidence limit of the reliable life under the test load spectrum is calculated as

$$\bar{x} = \frac{1}{5} \sum_{j=1}^5 \lg N_{B,j}^* = 4.2738 \quad (34)$$

$$\hat{\sigma} = \sqrt{\frac{1}{5-1} \sum_{j=1}^5 \left(\bar{x} - \lg N_{B,j}^* \right)^2} = 0.0676 \quad (35)$$

$$t_{\sqrt{5}u_{0.999,0.9}}(4) = 6.8464 \quad (36)$$

$$N_{B,RL}^* = 10^{\bar{x} - \frac{\hat{\sigma}}{\sqrt{5}} t_{\sqrt{5}u_{0.999,0.9}}(4)} = 7252 \text{ (blocks)} \quad (37)$$

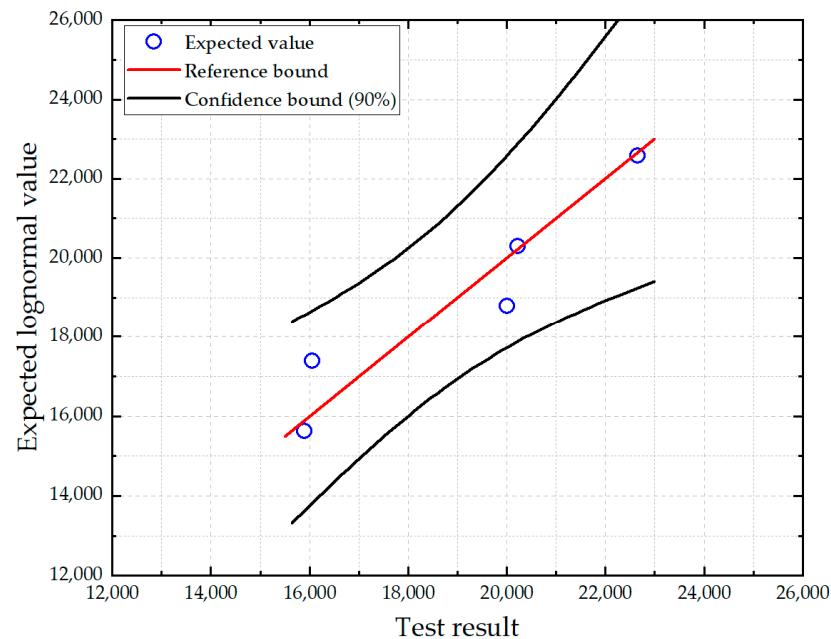


Figure 7. The lognormal Quantile-Quantile plot of test life of the central wing joint panel.

In aircraft fleet management, all aircraft will be managed with the above estimation result, ignoring the usage load difference of each aircraft.

In addition, the point estimate of the structure's median life is also given for comparison in the following text. Let $R = \gamma = 0.5$, it can be calculated as

$$\hat{N}_{B,50}^* = 10^{\bar{x}} = 18,784 \text{ (blocks)} \quad (38)$$

5.2. P-S-N Curve Assessment

The P-S-N curve is needed for the structure's reliable life consumption and individual aircraft life monitoring. According to reference [29], the slope parameter of the structure's P-S-N curve is

$$m_R = 3.89 \quad (39)$$

According to Equation (17), the P-S-N curve parameter C_R can be calculated as

$$C_R = N_{B,RL}^* \sum_{i=1}^{10} n_i^* (S_i^*)^{m_R} = 1.81 \times 10^{15} \quad (40)$$

Then the P-S-N curve of the central wing joint panel with $R = 0.999$ and $\gamma = 0.9$ can be calculated as

$$N_{RL} S^{3.89} = 1.81 \times 10^{15} \quad (41)$$

In addition, the median S-N curve is also estimated for comparison in the following text. Let $R = \gamma = 0.5$; it can be calculated as

$$\hat{N}_{50} S^{3.89} = 4.68 \times 10^{15} \quad (42)$$

According to Equations (41) and (42), the lower confidence limit of reliable life $N_{RL,i}^*$ ($R = 0.999$, $\gamma = 0.9$) and point estimate of median life $\hat{N}_{50,i}^*$ ($R = \gamma = 0.5$) under each fatigue load in Table 2 can be calculated. The calculation result is listed in Table 3.

Table 3. The estimated reliable life under each fatigue load in the test spectrum.

i	$S_i^*/(\text{MPa})$	Lower Confidence Limit of Reliable Life $N_{RL,i}^*/(\text{Cycles})$	Point Estimate of Median Life $\hat{N}_{50,i}^*/(\text{Cycles})$
1	650	2.06×10^4	5.35×10^4
2	585	3.11×10^4	8.07×10^4
3	518	4.99×10^4	1.29×10^5
4	453	8.41×10^4	2.18×10^5
5	348	2.34×10^5	6.04×10^5
6	282	5.31×10^5	1.38×10^6
7	249	8.62×10^5	2.22×10^6
8	215	1.53×10^6	3.93×10^6
9	175	3.40×10^6	8.83×10^6
10	132	1.02×10^7	2.65×10^7

5.3. Verification of Individual Aircraft Life Monitoring under Test Load Spectrum

Compared with aircraft fleet management, the progressiveness of individual aircraft monitoring is that it considers the actual service load of individual aircraft. However, the two methods should achieve the same result when the actual service load is same as the test load. This can be used for the verification of the proposed method.

Suppose that an individual central wing joint panel has worked under the test spectrum in Table 2 for 7252 blocks. Then, three methods are discussed below.

For the aircraft fleet management method, the reliable life determination result is $N_{B,RL}^* = 7252$ blocks with reliability requirements of $R = 0.999$ and $\gamma = 0.9$. When the central wing joint panel works for 7252 blocks, it cannot work before life extension.

For the individual aircraft monitoring method in this paper, the reliable life consumption percentage and remaining reliable life percentage of the central wing joint panel are calculated as

$$L_{CUt} = 7252 \times \sum_{i=1}^{10} \frac{n_i^*}{N_{RL,i}^*} = 100.0\% \quad (43)$$

$$L_{RLt} = 1 - L_{CUt} = 0.0\% \quad (44)$$

It means that this central wing joint panel cannot still work under any fatigue loads with the requirements of $R = 0.999$ and $\gamma = 0.90$. The conclusion is the same as that of the aircraft fleet management method.

For the conventional life-consumption-based individual aircraft monitoring method, the life-consumption percentage of the central wing joint panel is calculated as

$$L_{Ct} = 7252 \times \sum_{i=1}^{10} \frac{n_i^*}{N_{50,i}^*} = 38.7\% \quad (45)$$

It means that this central wing joint panel can still work, which is inconsistent with the aircraft fleet management method and dangerous in engineering.

The above calculation conclusions are listed in Table 4. It indicates that the proposed method in this paper is entirely consistent with the aircraft's reliable life determination with high confidence and reliability. This is because:

- (1) Individual aircraft life monitoring is conducted based on reliable life consumption with high reliability and high confidence, while the same reliability values are required in the aircraft's reliable life determination.
- (2) The P - S - N curve used for reliable life consumption is obtained based on the aircraft structure's full-scale life test, while the aircraft structure's life determination is also conducted through the full-scale life test.

Conventional individual life monitoring methods based on life consumption lack adequate consideration of confidence and reliability. It can be seen from above that confi-

dence and reliability must be simultaneously considered. Otherwise, individual aircraft life monitoring will be disconnected from high-confidence and high-reliability requirements in the aircraft's reliable life determination and extension.

Table 4. Comparison of aircraft fleet management and individual aircraft life monitoring under test load spectrum.

Aircraft fleet management method	Proposed individual aircraft monitoring method	Conventional life-consumption-based individual aircraft monitoring method
Work is not allowed after 7252 blocks	Work is not allowed after 7252 blocks	Work is allowed after 7252 blocks

5.4. Comparison of Individual Aircraft Life Monitoring and Aircraft Fleet Management under Service Load

Suppose that an individual aircraft has worked for 5122 flight hours during outfield service. The fatigue load of its central wing joint panel is monitored in real time. Table 5 lists its average fatigue load history during one flight hour. And the lower confidence limit of its reliable life under each fatigue load is calculated through Equation (41) and also listed in Table 5.

Table 5. Average service load history of an individual central wing joint panel during one flight hour (stress ratio $r = 0$).

i	S_i /(MPa)	n_i /(Cycles)	Lower Confidence Limit of Reliable Life $N_{RL,i}^*$ /(Cycles)
1	589	0.15	3.03×10^4
2	531	0.58	4.53×10^4
3	502	2.01	5.64×10^4
4	376	2.13	1.74×10^5
5	297	3.59	4.34×10^5
6	261	6.65	7.18×10^5
7	217	5.58	1.47×10^6
8	210	19.82	1.67×10^6
9	171	29.34	3.72×10^6
10	123	44.29	1.34×10^7

Based on Equation (25), the upper confidence limit of the reliable life consumption percentage with $R = 0.999$ and $\gamma = 0.90$ can be evaluated as

$$L_{CUt} = 5122 \times \sum_{i=1}^{10} \frac{n_i}{N_{RL,i}^*} = 56.2\% \quad (46)$$

Then the lower confidence limit of the remaining reliable life percentage with $R = 0.999$ and $\gamma = 0.90$ can be evaluated as

$$L_{RLt} = 1 - L_{CUt} = 43.8\% \quad (47)$$

Compared with this, all aircraft will be managed with $N_{B,RL}^*$ in the aircraft fleet management, ignoring the usage load differences of each aircraft. The structure's determined reliable life in aircraft fleet management is 7252 flight hours, and the work time of the individual aircraft is 5122 flight hours. It means that $5122/7252 = 70.6\%$ of reliable life has been used, while only 29.4% (2130 flight hours) remains. The calculation results are listed in Table 6. In this case, the aircraft fleet management will underestimate the aircraft's life potential by $70.6\%/56.2\% = 1.26$ times, causing economic waste.

Table 6. Comparison of aircraft fleet management and individual aircraft life monitoring under service load in Table 5.

Aircraft fleet management method	Proposed individual aircraft monitoring method
70.6% of reliable life has been consumed	56.2% of reliable life has been consumed

Furthermore, if the service load of another individual aircraft is too severe, aircraft fleet management might be dangerous. For example, suppose that another individual aircraft has also worked for 5122 flight hours during outfield service. The fatigue load history of its central wing joint panel during one flight hour is listed in Table 7. In this case, the upper confidence limit of the reliable life consumption percentage with $R = 0.999$ and $\gamma = 0.90$ can be evaluated as

$$L_{CUt} = 5122 \times \sum_{i=1}^{10} \frac{n_i}{N_{RL,i}} = 92.5\% \quad (48)$$

However, the aircraft fleet management method still believes that only 70.6% of reliable life has been used. The calculation results are listed in Table 8. It can be seen that the aircraft fleet management will overestimate the aircraft's life potential by $92.5\%/70.6\% = 1.31$ times, making the aircraft dangerous.

Table 7. Average service load history of another individual central wing joint panel during one flight hour (stress ratio $r = 0$).

i	$S_i/(\text{MPa})$	$n_i/(\text{Cycles})$	Lower Confidence Limit of Reliable Life $N_{RL,i}^*/(\text{Cycles})$
1	625	0.20	2.06×10^4
2	588	1.08	3.11×10^4
3	562	2.26	4.99×10^4
4	393	3.53	8.41×10^4
5	326	6.07	2.34×10^5
6	299	5.96	5.31×10^5
7	245	5.09	8.62×10^5
8	208	18.03	1.53×10^6

Table 8. Comparison of aircraft fleet management and individual aircraft life monitoring under service load in Table 7.

Aircraft fleet management method	Proposed individual aircraft monitoring method
70.6% of reliable life has been consumed	92.5% of reliable life has been consumed

This section provides a simulation example for the comparison between the proposed individual aircraft life monitoring method and the aircraft fleet management method under two cases: mild service load (Table 5) and severe service load (Table 7). In engineering practice, the specific comparison effect will depend on the actual aircraft load difference.

5.5. Online Life Management of Individual Aircraft

The remaining reliable life management of individual aircraft can also be realized online. A simple simulation example for mission arrangement is given below.

Suppose that two mission types need to be conducted for the individual aircraft with $L_{CUt} = 56.2\%$ and $L_{RLt} = 43.8\%$ in Section 5.4. If the upper confidence limit of the structure's reliable life consumption percentage caused by Mission 1 is known as $L_{CU,1} = 0.1\%$, then the aircraft can continue to perform the mission for $L_{RLt}/L_{CU,1} = 438$ times with the required reliability of $R = 0.999$ and $\gamma = 0.90$. The upper confidence limit of the structure's reliable life consumption percentage by Mission 2 is known as $L_{CU,2} = 0.2\%$, then the

aircraft can continue to perform the mission for $L_{RLt}/L_{CU,2} = 219$ times with the required reliability. According to the actual demand, as shown in Figure 8, mission combinations can also be reasonably arranged.

By doing so, the active control of the individual aircraft can be realized.

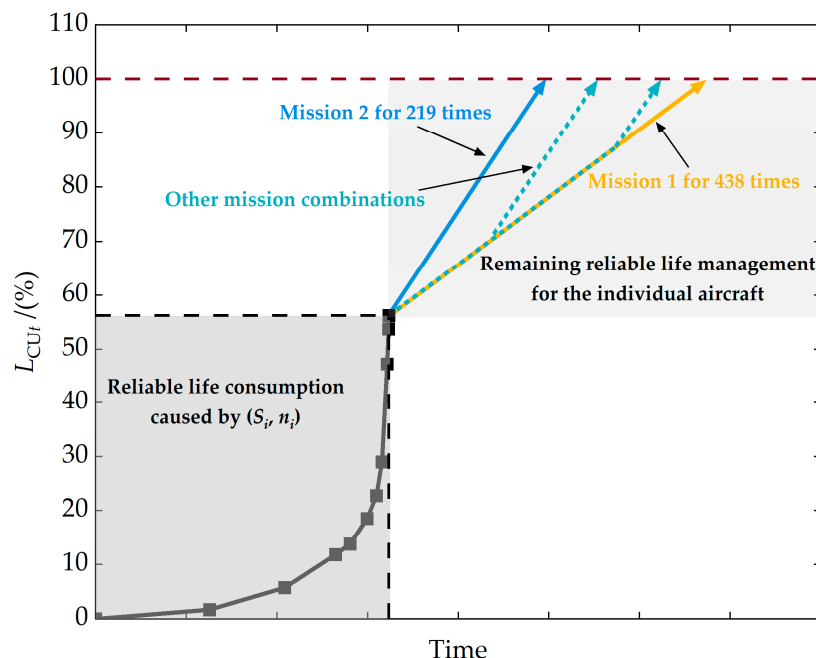


Figure 8. The reliable life consumption percentage and subsequent mission arrangements.

6. Conclusions

A novel individual aircraft life monitoring method based on reliable life consumption assessment is proposed. It can evaluate the upper confidence limit of the reliable life consumption percentage and the lower confidence limit of the remaining reliable life percentage in real time according to the aircraft structure's fatigue load history or flight missions during service. When the reliable life consumption percentage reaches 1.0 or the remaining reliable life percentage reaches 0, the aircraft structure should be planned for scrapping or life extension.

Furthermore, different mission types correspond to different loads and damages. Therefore, according to the aircraft's remaining reliable life and reliable life consumption caused by different mission types, online life management work such as mission arrangement can be reasonably conducted to ensure its safety and exploit its life potential simultaneously.

The conventional life-consumption-based individual aircraft monitoring method lacks reliability consideration, and this paper solves this problem. The case study and discussion indicate that reliability and confidence must be considered simultaneously, and the proposed method is consistent with the aircraft's reliable life determination and extension work with high confidence and high reliability, widely accepted in engineering practice nowadays.

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