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Individual aircraft life monitoring: An engineering approach for fatigue damage evaluation

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Abstract Individual aircraft life monitoring is required to ensure safety and economy of aircraft structure, and fatigue damage evaluation based on collected operational data of aircraft is an integral part of it. To improve the accuracy and facilitate the application, this paper proposes an engineering approach to evaluate fatigue damage and predict fatigue life for critical structures in fatigue monitoring. In this approach, traditional nominal stress method is applied to back calculate the *S-N* curve parameters of the realistic structure details based on full-scale fatigue test data. Then the *S-N* curve and Miner's rule are adopted in damage estimation and fatigue life analysis for critical locations under individual load spectra. The relationship between relative small crack length and fatigue life can also be predicted with this approach. Specimens of 7B04-T74 aluminum alloy and TA15M titanium alloy are fatigue tested under two types of load spectra, and there is a good agreement between the experimental results and analysis results. Furthermore, the issue concerning scatter factor in individual aircraft damage estimation is also discussed.
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1. Introduction

When an aircraft fleet is put into service, realistic loads experienced by each aircraft vary significantly with different operational environment such as weather conditions, runway quality and skill of pilots. Different operational load histories lead to variations in fatigue damage accumulated in each aircraft structure.[1] If the difference between realistic load history and that previously stated is neglected, two problems may arise:

(1) Structural safety may be adversely affected. If the realistic load spectrum is more severe than the designed one, cracks may occur earlier than the repair point of critical locations, thus leading to structural fatigue failure.
(2) The economy of aircraft may also be compromised. If the realistic load spectrum is mild and the management of fleet still follows an average damage estimation, the aircraft may be retired prior to its life span.

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To ensure the safety and economy of aircraft, it is thus necessary to implement individual aircraft monitoring when a fleet is put into service. With operational data collected, fatigue life expended and remaining life of aircraft structures can be estimated.[2]

Fatigue monitoring of individual aircraft involves operational data collection, load spectrum development, damage estimation, fatigue life prediction and management.[3] The existing literature on it is extensive[2,4,5] and plenty of methods have thus far been developed for operational data collection and fatigue life management.[6–10] Generally realistic load history can be accurately monitored using flight parameter-based method or strain gauges at critical points, complemented by fatigue test calibration and data processing.[11,12] Pertinent approaches regarding fatigue damage analysis fall into two categories: fatigue analysis-based method and crack growth analysis-based method;[13] however, there are limitations in application of both methods. For fatigue analysis-based method,[14–16] empirical parameters are often used to determine the fatigue quality of structure details, which may result in low accuracy since those parameters fail to reflect real structural status. Although crack growth analysis-based methods can improve accuracy, this method is complex to be applied and the analysis results remain to be validated by fatigue tests as those models cannot appropriately account for load interaction.[17–19]

Accurate fatigue damage evaluation for critical structures in service is the core of fatigue monitoring. To solve the existing problems, a strain-based fatigue crack initiation model is proposed in Ref. [20] to calculate fatigue damage accumulated on wing root under individual spectra. Test-analysis correlations show that this model is suitable for tension dominated load spectra, but the case with significant compressive loading remains to be refined. Besides, the strip-yield model was applied to calculate the total life in Ref. [20], with pertinent parameters obtained from test results. However, in the implementation of this model, empirical adjustments are needed when different long spectrum histories are considered. Although the flight-by-flight approach proposed in Ref. [21] incorporates load sequence and load interaction effects, further development and evaluation are required to assess its applicability in predicting fatigue crack growth under untested spectra for different materials. Therefore, an accurate, efficient and practical approach is required for damage estimation and fatigue life prediction in fatigue monitoring. In this paper, firstly the fatigue analysis model is developed using full-scale fatigue test data. Then, fatigue test and data analysis are conducted to verify the applicability of this approach. Finally, an application of the proposed approach is illustrated.

2. Requirements for fatigue monitoring of individual aircraft

Several requirements are needed to conduct fatigue monitoring for individual aircraft:

(1) Mechanical properties of related materials are obtained, including the elasticity modulus, yield strength, tensile strength, *S-N* curve, etc.
(2) The load spectra for full-scale fatigue tests are definitely determined. During the aircraft structural development stage, the load spectra for full-scale fatigue tests are compiled based on relevant theories and experience, and the load spectrum for each critical structure can therefore be obtained.
(3) Regarding the fatigue life of aircraft structures, full-scale fatigue test data are complete and comprehensive. During the final stage of aircraft structural design, full-scale fatigue tests are conducted under the predetermined load spectrum to identify critical locations and obtain pertinent crack growth information.
(4) Realistic load spectra for individual aircraft can be developed based on the operational data.

3. Engineering approach for fatigue damage evaluation

Since reliable load spectra of critical structures can be obtained through fatigue monitoring, a stress-based fatigue analysis model is developed for damage estimation and fatigue life prediction.

3.1. Issues in traditional nominal stress method

3.1.1. Analysis procedure

For the traditional nominal stress method, nominal stress traces are rainflow cycle counted, in which peaks and valleys are paired into cycles. For cycles with non-zero mean stresses, equivalent fully-reversed stress amplitudes are then determined using the constant life curve. The damage for each cycle is calculated with material *S-N* curve, and the total fatigue damage is accumulated with Miner's rule. In addition, safe life can be calculated by the quotient of fatigue life and fatigue scatter factor. The analysis procedures[22] are shown in Fig. 1.

3.1.2. Issues in traditional method

Factors significantly affecting the accuracy of damage estimation are as follows:

(1) *S-N* curve parameters of structural details. Based on a series of material *S-N* curve, the interpolating method is used to obtain the *S-N* curve for realistic structural details, considering material status, loading condition and surface quality as correction factors. However, those factors are generally acquired from experience, which may fail to reasonably reflect the real fatigue properties of structural details.
(2) Limitation of current cumulative damage theories. Plenty of theories and experimental researches[23,24] show that linear cumulative damage theory fails to account

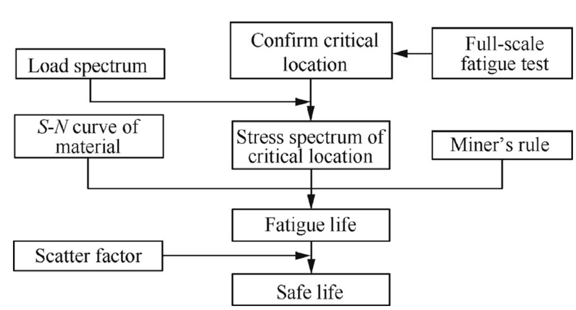

Fig. 1 Analysis procedure for traditional nominal stress method.

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