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Probabilistic and testing analysis for the variability of load spectrum damage in a fleet ☆

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ABSTRACT

Scatter of fatigue life of a fleet is mainly caused by the variability in structures and load spectra. To ensure the safety in service, the probabilistic characterization of load spectrum variability should be researched in durability analysis and testing work. This paper investigates the variability of load damage rate of a fleet. Based on the flight historical parameters measured by individual aircraft tracking (IAT) from hundreds of aircrafts for a certain type of fighter in China, SWT formula and linear damage rule are used to evaluate the load damage, and then, one average and four other individual load spectra are selected corresponding to different damage severities. Fatigue tests are conducted with the Aluminum alloy 7B04-T74 specimens under five spectra and the Titanium alloy TA15M specimens under three of them. The engineering crack initiation lives are measured and the mean lives are estimated assuming the fatigue life following a log-normal distribution. An obvious difference of at least 2.4 times in the load damage rates is found in the fleet. The fatigue lives of a fleet of aircrafts are calculated by Neuber's approach, and the probabilities refer to damage severities of those 5 load spectra in a fleet are evaluated. The statistical analysis of the fatigue lives and the probabilities shows that a lognormal distribution can be used to describe the variability of load damage rate of a fleet. The variation of the load damage rate is in the same order of magnitude with that in structural properties.

1. Introduction

To ensure the safe usage of aircraft structures, the reliability life should be evaluated analytically and tested in design stage according to the strength requirements for aircraft structure in specifications or standards [1–3]. It is well known that the fatigue life of a fleet is inherently varying due to various factors, which can be mainly divided into two categories: structural variability and load spectrum variability [4–6]. A need exists to account for the effects of both the variabilities on the fatigue life.

Structural variability refers to the statistical variability inherent in the fatigue performance of built-up structures which arises from the variability in material properties, manufacturing and assembly processes, etc, and it is usually quantified by the probability distribution of the fatigue life under a prescribed load spectrum. Since the reliability theory of fatigue was established many decades ago [7,8], several continuous probability functions and corresponding parameters have been used to delineate the variability of the fatigue properties of commonly used metallic structures [8–10].

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Load spectrum variability of a fleet refers to the differences of load-time history among the aircrafts of the same type and usage. It may occur due to differences in the pilot's expertise, climate, runway, the aircraft's weight, etc. Comparing with structural variability, it is more difficult to determine the variability in load spectra because the conditions in service are complicated and the measurement of load parameters is time-consuming and costly [11]. In recent years, a large number of load-time historical parameters have been characterized with the wide utilization of individual aircraft tracking (IAT), and more attention is focused on the load spectrum variability. Generally, there are two ways to express it: (1) the variability of load-time historical parameters between individual aircrafts within a fleet [12–15]; (2) the variability of the damage rate related to load spectrum. The damage rate refers to the fatigue damage per flight hour which could be used to study the influence of load spectrum on the variability of fatigue life. Based on the load data from IAT for key structures, the load spectrum damage rates of individual aircrafts in a fleet can be calculated and then a suitable random variable will be used to describe the variability of damage rate [15–20]. Since there is not an accepted distribution function for the load damage rate, it is necessary to investigate its variability by analysis and testing.

In order to develop a suitable load spectrum, lots of fatigue tests are conducted to draw a comparison and clarify the difference between various methods developed [21–23]. Fatigue tests are also used to assess the relative severity of a design spectrum against the actual service spectrum [24]. However, reports about systematic testing research on the variability of load damage rate for a fleet have not been found yet.

Based on the tracking load data from a certain type of fighter in China, in this study, individual load spectra for hundreds of aircrafts are developed, in which five load spectra corresponding to different damage severities are selected. The fatigue tests are conducted with the Aluminum alloy 7B04-T74 specimens under those five load spectra and the Titanium alloy TA15M specimens under three of them. The engineering crack initiation lives are then analyzed statistically to investigate the variability of load damage rate of a fleet.

2. Calculation and statistical analysis on the load damage rate

2.1. Collection of flight parameters

A recording system consists of sensors, data collection and processing device, signal tape recorder was used to measure flight parameters of a fighter in China. The signals from sensors are edited and then recorded by the magnetic tape recorder. After landing, the recorded information are imported into the computers on the ground at weekly or monthly intervals, and then, the recorded data are reverted to original historical parameters by using a special software for further processing and analysis.

The recording system performs a continuous scanning of several parameters related to load, mainly including flight time, airspeed, altitude, normal acceleration, lateral acceleration, fuel remained, attack angle, pitching angle, sideslip angle, grade angle, as well as the position of aileron, horizontal stabilizer, leading edge slot, rudder, etc. The sampling rate of above mentioned parameters is 1$\sim$8 times per second, specially, 8 for accelerations.

A very large set of recorded data have been accumulated for hundreds of aircrafts by using this system.

2.2. Data processing of flight parameters

The data processing of flight parameters for each fighter can be briefly described as the following steps:

(1) Data editing. The spurious data collected is detected and eliminated to ensure the reality and reliability of flight parameters of individual aircrafts;
(2) Data reduction. The middle points between the peak and trough accelerations are removed, and effective values at a series of peaks and troughs in a load parameter–time history are obtained.
(3) Data compression. After obtaining the data corresponding to above effective peak and trough points, in order to reduce the load cycles applied, some small acceleration cycles are filtered since their influence on the fatigue damage of airplane structures are insignificant.
(4) Effective acceleration analysis. Accounting for the weight of aircraft stores and the fuel consumed, the instantaneous effective weight corresponding to the acceleration $n_z(i)$ filtered in step (3) can be calculated and written down as $G(i)$ which is used to correct the normal acceleration at the center of gravity. Supposing the standard weight of aircraft to be $G(0)$, the effective normal acceleration accounting for the influence of aircraft weight will be evaluated as

$$n_{z,e}(i) = n_z(i)\frac{G(i)}{G(0)} \tag{1}$$

Therefore, the data for effective acceleration–time history can be determined.

Based on the data of flight parameter–time history measured by IAT for hundreds of aircrafts in China, the effective acceleration spectra of all aircrafts are developed [25].