GAP-FILL METHODS FOR ESTIMATING FATIGUE DAMAGE

Submitted to the 7th Joint DoD/FAA/NASA Conference on Aging Aircraft
September 8-11, 2003
New Orleans, Louisiana

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Abstract

The fatigue damage calculated for an aircraft by the Individual Aircraft Tracking (IAT) programs is dependent on the quality of input data. When the input data quality is poor or invalid, aircraft operators resort to gap-filling techniques to account for missing or invalid data. Invariably, conservative estimates of fatigue damage are obtained by imposing severe penalties for invalid or missing data, which leads to early retirement of aircraft when there is a large amount of gap-fill. In an environment where there is a demand to keep flying older aircraft, it becomes essential to assess the amount of gap-fill and the gap-fill technique used in the Individual Aircraft Tracking (IAT) programs to estimate fatigue damage for invalid or missing data.

This paper first addresses common problems with the aircraft data and its causes. The paper then examines usage and damage based gap-fill techniques that are used in IAT programs with a focus on fatigue damage assessment and then provides relative merits of gap-fill techniques. The paper proposes a modified damage gap-fill method based on mitigating the fleet-wide risk. The application of the proposed gap-fill method is then illustrated for a hypothetical fleet of aircraft.

1. Introduction

Whenever an aircraft has invalid or missing usage information for a given period of time, an approximate usage value must be supplied in its place to estimate fatigue damage for this period. This procedure is called gap-filling. The period of missing or invalid usage data is also termed gap-fill period.

Gap-filling has been practiced for many years since aircraft operators started monitoring aircraft fatigue through individual aircraft tracking programs. Early attempts at defining an aircraft useful service life were based solely on the number of hours a particular aircraft model was designed to fly. This practice had the implicit assumption that all aircraft in a particular fleet fly roughly the same way. As a consequence, most of the aircraft in these early fleets had to forfeit a considerable amount of their useful lives. Nevertheless, if this restriction was compromised, there was no way of telling which aircraft were the ones that needed to be retired. Hence the risk of an accident was considerable. To cope with this problem, individual aircraft usage had to be determined. Onto this extent different types of recording devices were mounted on aircraft and so fatigue tracking was established. Logbooks were used as compliments to these devices and in many instances as sole indicators of aircraft usage. Since the start of aircraft fatigue tracking, a large diversity of recording devices have been produced and the methods of tracking have become more sophisticated. In theory, this was all that was needed in order to track aircraft individually and get the most out of their useful lives Unfortunately, these improvements also led to a false sense of security and an over-reliance on instruments. In practice, however, instruments go off-line, are miscalibrated and/or record incorrect values. This poses a formidable task in the area of quality control, and once the recorded data goes through this stage, it is commonplace to find gaps in the information string. Even when the instruments are working properly, the data may simply get lost or damaged somewhere along the long chain of personnel that have to retrieve, transport, store, process and approve the data. It is the misconception that information gaps are small relative to the life of the aircraft that has encouraged the practice of using quite conservative estimates during gap-fill. In reality however, gaps may account for the majority of an aircraft's life. Figure 1 schematically shows gaps in aircraft data collected over time.

Attempts to make gap-filling more accurate and improve life predictions stems from the current requirements of utilizing full service life of aging aircraft fleet as it is no longer affordable to dismiss aircraft useful service life by overly penalizing faulty data. In this context of improving the accuracy life predictions during gap-fill, there is a greater need to define an acceptable level of risk for the fleet during gap-fill. In general, there is no standard governing risk-based gap-filling information since each aircraft platform is different from the standpoints of usage, operating loads environment, method and type of data collected and processed etc.

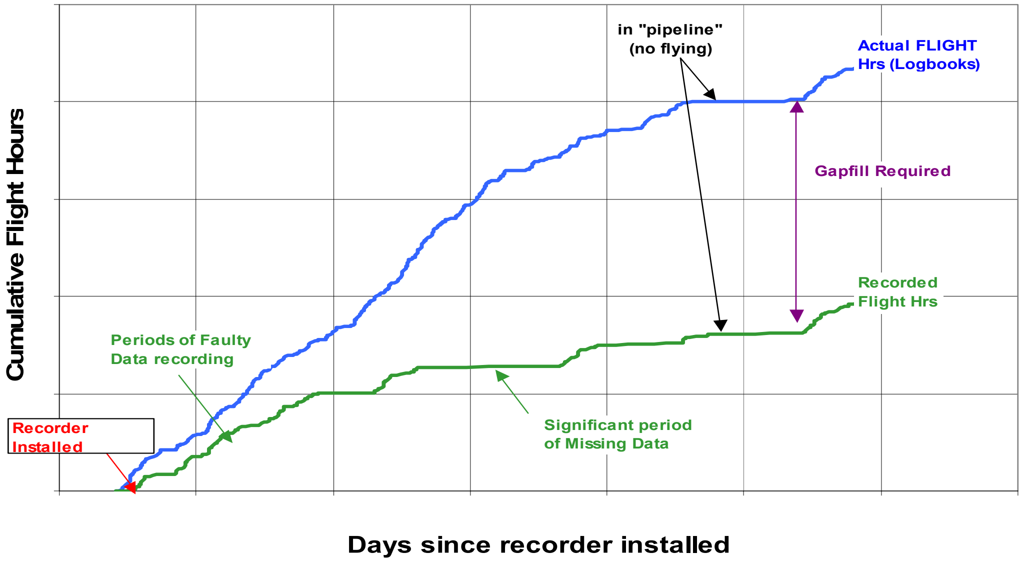

Figure 1. Schematic of data collected over time

In this paper, the subject of gap-fill is discussed with fatigue damage estimations as the main focus. However, this is quite relevant to life estimation procedures using fracture mechanics approaches as missing or invalid information is common in usage data. The paper first addresses the gap-fill subject by describing corrupt or faulty usage data and some reasons for it. This is followed by a discussion on conventional methods of gap-fill and general observations from using these methods in life predictions. A gap-fill method using risk-based criteria is then proposed and illustrated for a hypothetical fleet of aircraft.

2. Faulty Data

The aircraft usage data collected by the operators falls into two categories: logbook records and instrumented data records. The instrumented data records are usually of two types: (a) single channel load factor exceedance records (counting accelerometer group (CAG) records), and (b) time sequenced multi-channel flight data records. The logbook records usually contain pilot entered information for each flight and contain aircraft configuration, flight duration, type and number of landings, etc. The logbook records have less entry errors and are usually of a high quality. The CAG and flight data recorder data are more prone for error either because of human intervention or component malfunction. In the case CAG records, data have to be transcribed on to paper from the instrument readings on the aircraft and is the main cause of entry errors. In the case of flight data recorder, it is usually component, channel, or software malfunction causing data errors. The following lists some examples of errors found in these records.

Counting Accelerometer Group (Nz Recorder Data)
1. Invalid Window Reading Entries (human
2. Consistency and Conformity of Data (positive increments over time and consistent exceedance counts from low to high g levels)
3. Stuck Window Readings – Electrical or Component Failure
4. Resets due to Indicator and Transducer Changes

Multi-Channel Flight Data Recorder
1. Channel Recording Errors (BIT Errors) Faulty Nz, Altitude, Air Speed, …
2. Criteria Errors Landing Error, Takeoff Error, No Takeoff Record, Takeoff with improper WOW indicator, No landing record, WOW Error,….
3. Constancy Errors Constant Altitude, Air speed, fuel or a combination of these
4. Induced Errors Faulty Nz and other parameter spikes before landing and store ejections,…
5. Other Errors Data Retrieval, Storing, and Transfer Errors

3. Gap-Fill Methods

The conventional gap-fill methods are of two types: (a) usage data or front gap-fill and (b) damage or back gap-fill.

In the first method, attempts are made to fill the missing information by recreating the section of the load spectrum that is missing. In essential, load spectrum data (from'g', stress, or strain exceedances) is first estimated either by statistical means for the gap-fill period and then fatigue damage is calculated for the estimated data.

In the damage gap-fill method, an appropriate or equivalent damage is assigned for a gap-fill period without estimating load spectrum data. The amount of damage to be applied depends on aircraft flight hours, length of gap-fill period, and acceptable level of risk.

The advantages of the usage gap-fill method lie in the fact that the load spectrum history is constructed for the aircraft including the gap-fill period. This is specifically important for crack growth analysis, as full load spectrum is usually required. The usage data gap-fill can also be applied when aircraft are inducted into service when only small body of usage data is available. The disadvantages of this gap-fill method are that it is computationally inefficient and does not quantify risk involved during gap filling.

The damage gap-fill method provides computational advantage and provides a risk indicator to the operator. A typical conventional damage gap-fill method (Reference 1) follows a rule based on the damage/hour criteria as described in Figure 2. In addition, this method is applicable when substantial usage data has been collected in the fleet (required for simulations) and is very useful when re-baselining damage of fleet aircraft due to fatigue life assessment programs, new full-scale fatigue test, or fleet and tear down findings. This method also does not quantify risk for individual aircraft or fleet-wide risk.

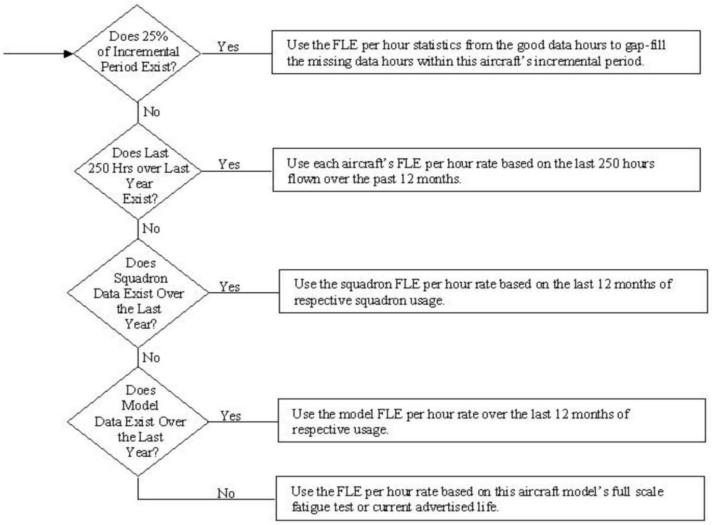

Figure 2. Typical Damage Gap-Fill Method

4. General Observations from Conventional Gap-Fill Methods

From our experience, the important point in proper usage-data gap-filling is a good understanding of major damage contributors for a given type of aircraft. For example, in a non-tactical aircraft, flight maneuver/gust and ground loads are major contributors of damage for most critical locations on major structures such as wing and fuselage. For a tactical aircraft, however, damage drivers are mainly flight maneuvers. So the number of flights to be gap-filled is more important for non-tactical aircraft than the flight time since ground-air-ground cycles are the major damage drivers. In most tactical aircraft, it is the flight time that is more important during gap-fill than the number of flights.

The usage-data gap-filling for CAG based aircraft is more straightforward than that for a multi-channel recorder based aircraft. In CAG based aircraft, the load factor exceedances for the gap-fill period has to be estimated by statistical means based on individual, squadron, or fleet-wide load factor exceedance data. Selection of a particular severity of load factor exceedances, whether it is 50th or 85th or 95th percentile load factor exceedances, for the gap-fill period is mainly driven by the perceived safety coverage required by the aircraft operator. However, when selecting a higher percentile load factor exceedances, care must be taken since higher 'g' levels may contribute to higher residual stresses impacting damage estimates. In the case of multi-channel recorder based aircraft, usage data reconstruction for the gap-fill period involves assembly of good flights from previous body of data (from the same, squadron, or fleet-wide aircraft as necessary) to match flights and hours within some tolerance. In both CAG and multi-channel based aircraft, usage data has to be reconstructed and damage has to be calculated using this data. One disadvantage of this method is that when the body of usage data collected is limited, deviation from true damage will be greater.

The damage gap-fill method does not involve usage data construction for the gap-fill period; instead an equivalent damage is assigned using previously calculated statistical damage rates. Usually for safety coverage, mean or mean plus some multiple of standard deviation of damage rates are used for gap-filling. This method is favored in some aircraft platforms because of its computational simplicity in individual aircraft tracking programs. In this method, if residual stresses are left uncorrected after gap-fill, conservative damage estimates will be obtained.

Another significant factor during gap-filling using the above methods is percentage data recovery. If the percentage data recovery for an individual, squadron, or fleet aircraft is poor, then estimated damage tends to be higher than the true damage because of the applied safety coverage applied during gap-fill periods. Simple examples have shown that estimated damages could be 2-3 times more than true damages because of very poor percentage data recovery.

In both gap-fill methods described above, there is no indication of what the true damage distribution of the fleet aircraft would be at any flight hours, thus the individual or fleet-wide aircraft risk can not be quantified. Also, these methods do not provide an up-front indication of the time to retire an aircraft if no usage data is available from that aircraft. To this effect, we describe a gap-fill method in the next section, which is a variant of damage gap-fill method that uses risk-based criteria in its core application.

4. Modified Damage Gap-Fill Method

The modified damage gap-fill we propose here utilizes a risk-based criterion as follows: The gap-fill method must ensure only a quantifiably small specified number or percentage of aircraft in a fleet would have a true damage greater than $1+d$ when the gap-filled damage is 1. The factor 'd' corresponds to a tolerance factor that could be unique to each aircraft platform, determined based on the knowledge that fracture or failure would occur some time after 2 times the crack initiation time.

For example, the above gap-fill criteria could be stated as follows for a hypothetical fleet as to require not more than 0.6% of the fleet aircraft to have a true damage exceeding 1.2 ($d=0.2$) when the predicted or gap-filled damage is 1.0.

The above criterion provides for a fixed fleet-wide aggregate risk over any age of aircraft however, it does not quantify individual aircraft risk at any time because of the basic definition of the criteria. However, this is an improvement over conventional damage gap-fill methods as risk from a fleet-wide standpoint is mitigated.

To implement this criterion, true fatigue damage distributions at different flight hours have to be first constructed. This cannot be constructed directly from actual fleet aircraft data since this invariably contains gaps in the usage data stream and also does not have data beyond certain flight hours. Hence, it becomes necessary to create a hypothetical fleet with all good usage data to determine true damage distributions. During this simulation one must ensure that usage data statistics match with that of actual fleet data. The true damage distributions for this simulated fleet aircraft will follow the general trend shown in Figure 3.

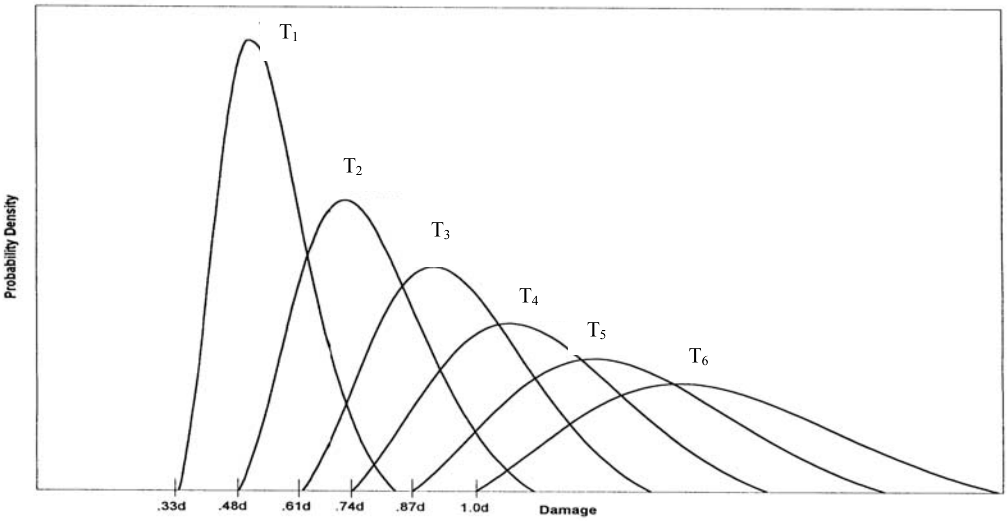

Figure 3. True Distribution of Damage Over Time

The above damage distributions, which are normally of Weibull type, indicate more spread in the distribution over time as a result of wide distribution in usage characteristics of fleet aircraft. Less visible, but of equal importance is the advance of the distribution on the horizontal axis. It is faster during early periods and slows down after to an almost steady value. Damage accrual rates are higher in the early periods because the residual stresses are not stabilized, as fleet aircraft would not have experienced all operating loads. At later periods, however, the damage accrual rates are lower because of stabilized residual stresses as fleet aircraft would have experienced most of the service operational loads.

In order to apply the above criterion, first we have to determine a reference time *(T)* at which only given percentage of the fleet aircraft (*0.6%* in the example criterion) have a true damage greater than *1+d* (*1.2* for the example criterion) when the gap-filled damage is *1*. This reference time, *T*, is also the retirement time of any aircraft whose usage is unknown (100% gap-fill), but whose usage is assumed to belong in the population considered for damage distributions. Then, gap-fill damage as a function of time must be established, which can be used to assign the damage to the gap-fill period. The gap-fill damage function must satisfy the boundary conditions at the zero and reference flight hours.

The reference flight hours, *T*, satisfying the gap-fill criterion can be obtained from the true damage distributions by reading damage values, $D_c(t)$, corresponding to the given criterion percentile of aircraft not exceeding the true damage value at retirement. In the example criterion, it is achieved by reading of damage values corresponding to *99.4%* ($D_{0.994}$) from each damage distribution curve (Figure 4), and then reading the $D_{0.994}$ value that corresponds to a damage of *1.2*.

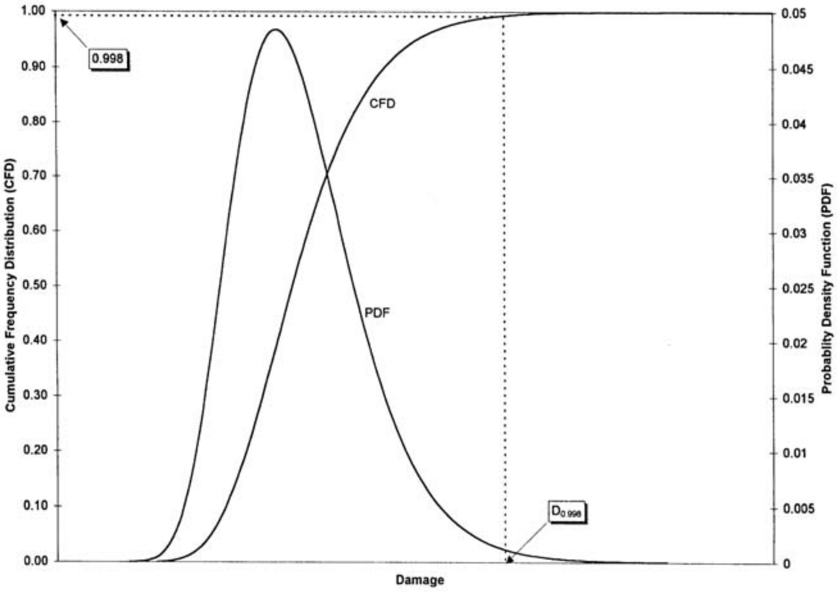

Figure 4. Illustration of $D_c(t)$ values from damage distribution curve

The gap-fill damage function, $D_g(t)$, or the gap-fill damage at any time is then calculated using the following relationship:

$$D_g(t) = D_c(t) - \delta(t), \text{ where } \delta(t) = \frac{dt}{T}.$$

The development of this relationship is given in the Appendix.

Figure 5 shows a schematic of the application of this method to a hypothetical attack aircraft showing the gap-fill damage curve. Figure 5 is also an illustration for the example criterion discussed in this section. It can be noticed that difference between the $D_c(t)$ curve and gap-fill damage curve increases from zero to a maximum of d at time *T*. This implies that if data is missing or invalid during the initial periods after aircraft are inducted, then damages for those periods are gap-filled severely at rates closer to $D_c(t)$ damage curve.

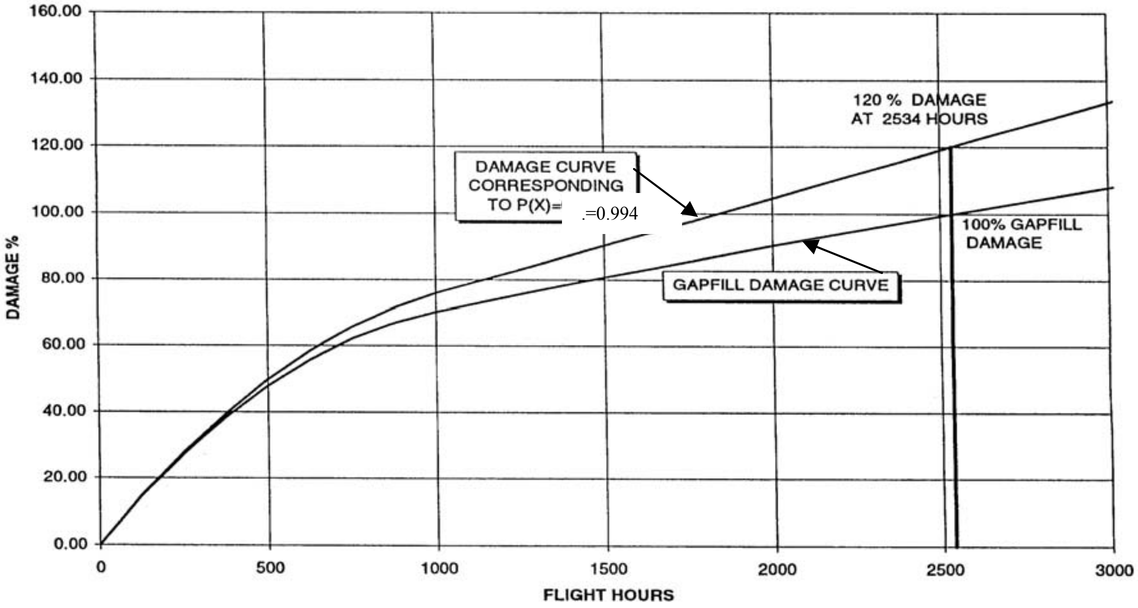

Figure 5. Illustration of gap-fill damage curve

The gap-fill damage curve can then be used to appropriately assign damage for missing periods using the begin and end-hours of the gap-fill period and then reading the increment damage between those hours from the gap-fill damage curve.

The residual stress as a function of time can also be determined from the results of true damage distributions such as shown in Figure 6. The residual stresses, which provide continuity between periods and thus account for prior history of loading, can also be adjusted following a gap-fill period using data from this curve.

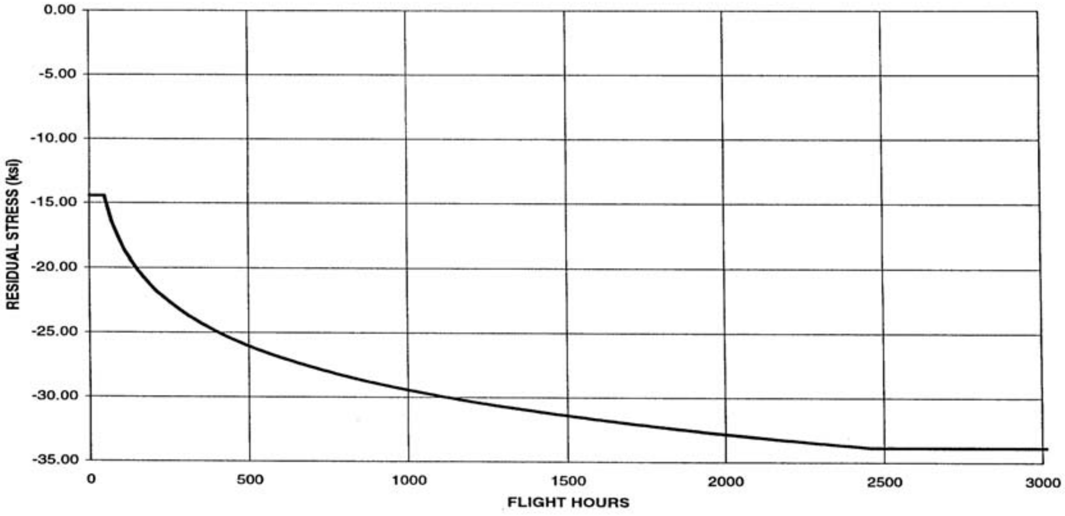

Figure 6. Residual Stress Variation

The above discussed damage gap-fill method satisfies the given criterion and thus ensures that only a given percentage of aircraft will have a true damage greater than *1+d* when the gap-filled damage is *1.0* for any percentage data recovery.

5. Discussion

The proposed gap-fill criterion is an improvement over the conventional damage gap-fill methods. However, this requires simulation of fleet usage data from known usage data statistics. Simulation of multi-channel recorder data is more cumbersome than that for single channel load factor recorder data, and hence this method is easily applicable to single channel load factor recorder data. Nevertheless, this method offers an advantage to determine the retirement time with a known risk quantity as expressed in the criterion statement. The problem that is not addressed with this method is how to minimize individual aircraft risk while also mitigating the fleet-wide risk.

The idea conveyed in this paper is crack initiation is very likely when fatigue damage is 1. The crack size at crack initiation time is usually considered as 0.01 inches. The probability of crack initiation at any time is thus equivalent to the probability of fatigue damage being equal to 1 at any time. Applying uncertainties associated with the fatigue model, material parameters and operating loads/stresses, and defining limit state functions, the probability of crack initiation may be calculated. However, this has to be verified by a vast body of service cracking data, and compared with results from probabilistic crack growth approaches. To carry out a complete risk based assessment of fatigue lives to facilitate inspection and maintenance planning, both probabilities of crack initiation and crack growth to a critical crack size have to be properly considered. This requires more detailed reliability based models to calculate risks associated with failure (involving both crack initiation and crack growth periods) of fleet aircraft with missing or invalid data.

6. Conclusions

This paper discussed conventional gap-fill techniques and their advantages and disadvantages from a fatigue damage estimation standpoint. A modified damage gap-fill method based on a risk-based criterion was proposed and a procedure to develop and apply this method was provided. This method is an improvement over the current damage gap-fill method by mitigating fleet-wide aggregate risk, but requires more development to address individual aircraft risk.

Acknowledgements

The authors would like to acknowledge the earlier contributions of Miguel Morales, Scott Leberknight and encouragement from David Cadman of NAVAIR and Charles Garber in developing portions of this paper. Thanks are also due to Mr. Robert Merrill of TDA, Inc. in reviewing and preparing some graphics in this paper.

References

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Appendix

Damage Gap-Fill Function

Consider the situation for an aircraft whose usage data is completely unknown. At the reference time *T*, the gap-filled damage value for this aircraft is set to *1* since only criterion-stated percent of fleet aircraft will have damage greater than $1+d$. Consider two aircraft with damages of *1* and $1+d$ from the damage distribution at reference time *T*. Clearly, these damage quantities coincide with the 100% gap-filled aircraft damage, $D_g(t)$, and the aircraft with the maximum criterion-allowable damage, $D_c(t)$, at time *T*. At any time $t<T$, the difference in damages, $\delta(t)$, between these two aircraft will be smaller, eventually becoming zero at zero time. This can also be observed from the damage distribution curves shown in Figure 1.

At any time t, the difference in damages between these two aircraft can be expressed as $\delta(t) = \int (R_h - R_l)dt$, where R_h and R_l correspond to the total damage rates of the aircraft with damages of $1+d$ and *1* at time *T*, respectively. Setting the difference R_h-R_l to a constant and applying the boundary conditions of $\delta = 0$ at $t= 0$ and $\delta = d$ at $t=T$,

$$\delta(t) = \frac{dt}{T}.$$

By observing that the difference $\delta(t)$ is the difference between $D_c(t)$ and $D_g(t)$, we obtain

$$D_g(t) = D_c(t) - \delta(t).$$

The gap-fill damage for any random aircraft for any time interval Δt can be extracted by the following relationship:

$\Delta D_g(t) = \Delta D_c(t) - \Delta\delta(t)$, which is equivalent to

$$\Delta D_g(t) = D_c(t_2) - D_c(t_1) - \frac{d(t_2 - t_1)}{T}.$$