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Probabilistic Damage Tolerance Methodology for Solid Fan Blades and Discs

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***Abstract*—**Solid fan blades and discs in aero engines are subjected to high combined low and high cycle fatigue loads especially around the contact areas between blade and disc. Therefore, special coatings (e.g. dry film lubricant) and surface treatments (e.g. shot peening or laser shock peening) are applied to increase the strength with respect to combined cyclic fatigue and fretting fatigue, but also to improve damage tolerance capability. The traditional deterministic damage tolerance assessment based on fracture mechanics analysis, which treats service damage as an initial crack, often gives overly conservative results especially in the presence of vibratory stresses. A probabilistic damage tolerance methodology using crack initiation data has been developed for fan discs exposed to relatively high vibratory stresses in cross- and tail-wind conditions at certain resonance speeds for limited time periods. This Monte-Carlo based method uses a damage databank from similar designs, measured vibration levels at typical aircraft operations and wind conditions and experimental crack initiation data derived from testing of artificially damaged specimens with representative surface treatment under combined fatigue conditions. The proposed methodology leads to a more realistic prediction of the minimum damage tolerance life for the most critical locations applicable to modern fan disc designs.

***Keywords*—**Damage tolerance, Monte-Carlo method, fan blade and disc, laser shock peening.

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I. INTRODUCTION

THE fan is the first rotor stage of the turbofan engine compressor. A brief summary of the design evolution is presented in [1]. It is driven by the development of material and manufacturing technologies to reduce the weight and to improve aerodynamic performance. Fan components are highly loaded by centrifugal forces causing low-cyclic fatigue (LCF) damage and airfoil vibration causing high-cyclic fatigue (HCF) damage. Both load components have to be considered in combination for the mechanical integrity assessment. The load combinations and especially the HCF contribution can be very different depending on a particular fan design. This paper focusses on solid fan blades and fan discs for small and medium turbofan aero engines made from Ti-6Al-4V (Ti 6/4). The typical design consists of blades with dovetail roots which interface with the corresponding dovetail slots in the fan disc. The dovetail design can be straight or curved and contains axial retention features (blade lugs or retaining plates). Approximately 80% of the thrust produced by the modern jet engine is delivered by the fan [2]. Therefore, the fan blades are some of the most critical engine components with respect to aerodynamic loads and resulting vibration. Integral or forced response fan vibration occurs at specific resonance speeds in the running range and is dependent on the natural frequencies of the Fan blades and installation effects, i.e. intake distortions. Wind speed and direction are the most important parameters affecting the blade vibration amplitudes. Therefore, engine operation on ground at adverse wind conditions while the aircraft is standing or rolling with low forward speed, e.g. maintenance runs can be most damaging in terms of forced response. Fan flutter [3] is a well-known non-integral, self-excited vibration mechanism, which is relatively well understood and mitigated in modern engines. Other non-integral excitation mechanisms [4] are less explored and the understanding of such phenomena is a developing research area.

The combined HCF and LCF loading condition causes high bending stresses in the blade root and also the disc dovetail and leads to fretting fatigue and wear in the contact areas between blade and disc. Fretting fatigue is one of the most frequently observed failure mechanisms for titanium fan blades and discs. Significant research activities were initiated to understand the phenomena and develop robust design concepts to mitigate this failure mechanism. Fretting fatigue failure initially begins as surface and near-surface damage caused by fretting in the form of significant plastic deformation of the surface, disruption of the surface oxide layer and material transfer [5]. These factors result in a substantial fatigue strength reduction compared to nominal components [5]. Fretting fatigue cracks are typically initiated in the Edge of Bedding (EOB) areas under partial slip conditions and can then propagate due to the normal loads. The mitigation of this failure mechanism includes:

- A reduction of steady and vibratory stresses, if at all possible
- Application of various coatings to reduce the coefficient of friction between blade and disc and to prevent material transfer and oxide layer deterioration [7]
- The introduction of efficient surface treatments like laser shock peening (LSP) or deep cold rolling (DCR) [2], [6].

Peening surface treatments introduce compressive residual stresses near the surface, microstructurally coupled with the formation of a work hardened near-surface layer [6]. The depth of the residual stress layer varies between 0,2 mm for conventional shot peening and 1,5 mm for LSP. Mechanical surface treatments provide a substantial improvement in

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fatigue capability compared to untreated base material. The level of improvement is dependent on the residual stress profile, the depth of the hardening layer and the degree of surface distortion obtained by the process. Surface treatments also improve resistance against wear and constitute a strong retardation mechanism for the cracks initiated in the contact areas or at EOB. The combination of the fan blade root / fan disc dovetail coatings and mechanical surface treatments is widely used in the aerospace industry. The validation and certification of such design solutions require:

- Finite Element analysis
- Specimen, component and sub-component tests to demonstrate fatigue capability of blade and disc with the selected coating/treatment system
- Strain gauge testing and/or aero elastic simulation to estimate vibration levels at various flight and ground maneuvers [8].

The prediction of the fatigue life for the component can then be performed using a deterministic or probabilistic approach.

Service induced damage tolerance is one of the criteria for certification of modern engines [9]. The traditional deterministic damage tolerance assessment is based on fracture mechanics analysis, i.e. service damage is treated as an initial crack. It often gives overly conservative results especially in the presence of vibratory stresses. Therefore, the traditional lifing methods for solid Fan blade roots and disc dovetails have to be developed further. A probabilistic damage tolerance methodology using crack initiation data for typical damages observed in service has been developed for fan discs and is presented in this paper.

The method is based on the previous LCF & HCF lifing model developed at Rolls-Royce by S. Hannaby and J. Schofield [8].

II. MONTE-CARLO DAMAGE TOLERANCE METHOD

The Monte-Carlo simulation is a widely used technique to estimate system responses resulting from known uncertain inputs. It provides a range of possible outcomes and their probabilities.

The key input parameters for the probabilistic damage tolerance analysis described in details later are:

- HCF stresses (amplitudes and exposure times) dependent on type of engine operation and wind conditions.
- Probability of service damage (e.g. scratch or nick) in critical location.
- Material properties.

The relationship between these input parameters and the generic set-up of the Monte-Carlo model is shown in Fig. 1.

Each specific type of operation results in exposure to certain vibration modes (time on condition) due to either dwelling in or transient crossing of the resonance bands. During these times on condition a certain number of cycles are accumulated (n^{HCF}). These can be calculated as the modal frequencies are well known from analysis and measurements.

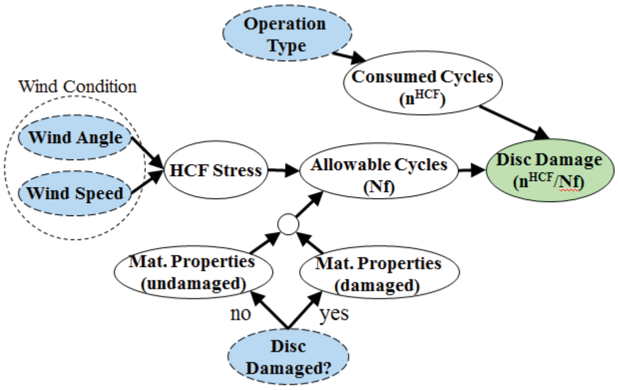

Fig. 1 Monte-Carlo Damage Tolerance Model

The Fan blade and consequently also the Fan disc vibratory stress levels (HCF stresses), i.e. the vibration amplitudes, are dependent on the wind conditions (wind angle with respect to the engine intake & wind speed). Relationships between wind and stress were derived from different strain gauge measurements during flight and bench test campaigns.

The Fan disc material properties (LSP treated Ti 6/4 in critical locations) are based on a dedicated specimen test program to investigate the effect of damages. The results are summarized in form of “stress-over-cycles to failure” (S-N) curves, also known as Wöhler curves. These are fed as input into the Monte-Carlo Model. They allow calculating the number of allowable cycles (Nf) for each combination of HCF stress and time on condition.

The HCF damage for each maneuver is the ratio of cycles spent on condition and allowable cycles (nHCF/Nf). Damage calculations are performed for each maneuver during all iterations of the Monte-Carlo run and finally summed. At each repetition another random wind angle and speed will be generated based on the input distributions, resulting in range of HCF stresses.

To account for the effect of service damages, i.e. damage tolerance, the model considers the probability of damage occurrence at the critical location and the properties of damaged material.

The output of the Monte-Carlo assessment is a distribution of the accumulated damages of a certain number of discs and for a predefined number of cycles (typically the declared safe cycle life of the disc in number of flight cycles). A damage value of $D = 1$ means crack initiation at the most critical disc location. For the final assessment a total damage must be considered that includes the HCF damage but also the LCF damage.

III. INPUT DATA

This chapter gives a detailed description of the input parameters for the Monte-Carlo Damage Tolerance Model, i.e. the HCF stresses as a result of wind conditions, operation types, probability of damage occurrence and the material properties obtained from the material test program of the pre-damaged Ti 6/4 material.

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A. *Critical Engine Operation Types*

As discussed above forced response fan blade vibration excitation is caused by intake distortions (flow separation) at adverse cross-wind conditions. Therefore, this effect only occurs under certain conditions when the engine is operated on ground while the aircraft is standing or rolling with low forward speed. At higher forward speeds on ground and obviously in flight the wind speed gets negligible and the intake cleans up, no flow separation can occur.

Engine operations on ground as defined in the aircraft test procedures and the engine manuals have therefore been reviewed for potential exposure to vibration excitations, i.e. maneuvers or types of operation that lead to dwell or transient crossings of critical resonance speed bands. These are mainly maintenance tasks, e.g. trim balancing runs, and engine test runs by the air framers. The number of times a certain operation will occur in the life of an engine and the times on condition for each occurrence were calculated (Fig. 4).

Similar damaging conditions but with shorter exposure times can potentially occur during the initial phase of take-offs. Analysis of flight data recorder data (FDR) of a large number of take-offs was performed to understand HCF exposure during take-offs.

B. *HCF Stresses*

The Campbell diagram (Fig. 2) illustrates the relationship between the modal frequencies of the Fan blade, the engine rotational speed and its harmonics. The example shows the frequencies of the first six blade modes (solid lines), e.g. 1st flap, 2nd flap etc. over the engine rotational speed. The dotted lines are the integral harmonics of the rotor speed, i.e. the engine orders (EO). The blade mode frequencies are changing with speed due to centrifugal loads and temperature.

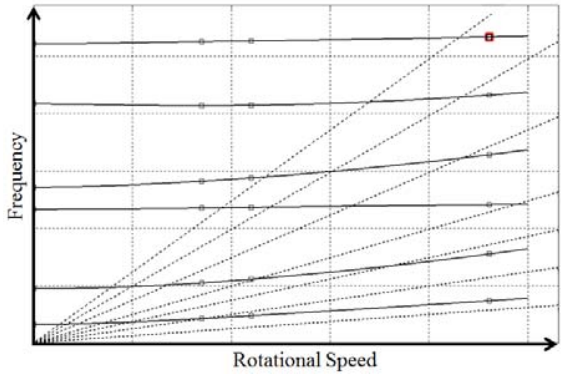

Fig. 2 Fan module Campbell diagram (example)

Intersections of modal frequencies with the rotor speed frequency or its harmonics indicate resonance speeds. Around these speeds the fan blades are prone to vibration excitation from inlet distortions.

Fan blade vibration stress surveys (Fig. 3) show the actual excitation behavior, i.e. measured amplitudes over engine speed. In certain speed ranges higher amplitudes are measured due to fan blade modal excitation. These resonance bands (incl. scatter) define the critical speed ranges for the modes of interest. Based on these resonance speed ranges the times on condition, i.e. transient crossing or dwelling within a resonance can be calculated for each operation type. Together with the known modal frequencies it is then possible to calculate the number of cycles accumulated in each resonance band for each type of engine operation. An example of an engine operation with transient and dwell conditions is shown in Fig. 4.

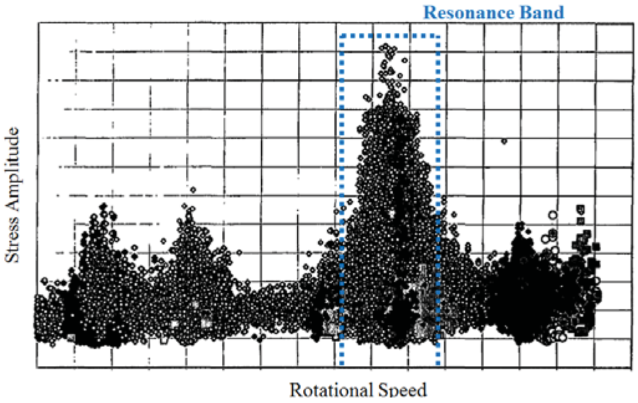

Fig. 3 Fan blade vibration response summary (example)

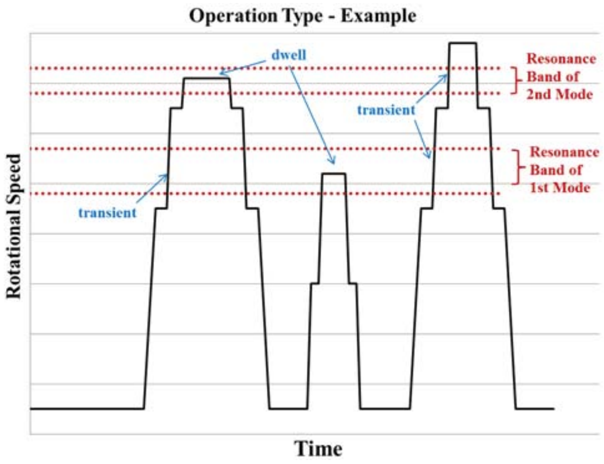

Fig. 4 Operation Type (Example)

The wind conditions such as wind speed and angle are essential for the amplitude of the mode vibration and consequently for the magnitudes of the vibratory stresses. As an example Fig. 5 shows the relationship between wind direction and measured stress amplitudes.

For the Monte-Carlo assessment the measured stress data was split in different (angle) sectors and for each sector a specific stress distribution was defined (Fig. 6). Once a random wind direction angle is defined a stress is taken from the stress distribution of the corresponding sector.

C. *In-Service Damage Survey*

An in-service damage survey was performed to identify on how many disc damages occurred in the critical area and what the damage dimensions were. The resulting damage rate was directly used as input for the damage tolerance assessment, i.e.

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with a specific probability the Monte-Carlo assessment uses material properties (S-N data) for undamaged or damaged material.

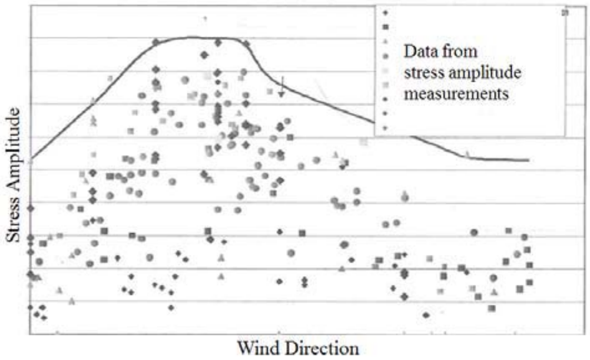

Fig. 5 Measured vibratory stresses over wind direction

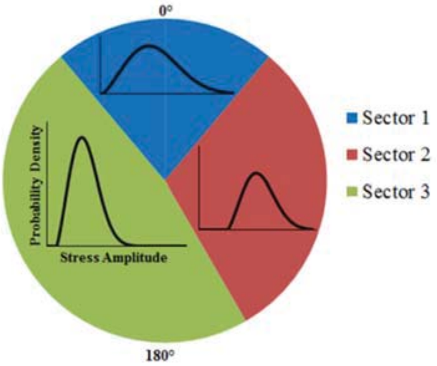

Fig. 6 Wind sectors with stress amplitude distributions

D. Material Test Program

For the calculation of the HCF damages for each operation and vibration exposure it is required to have material properties (S-N curves) for undamaged and damaged Fan disc material (LSP treated Ti 6/4). Properties for undamaged Fan disc material were already available. Those were derived from a dedicated specimen test program [8]. A similar program was performed to investigate the effect of service damages on LSP treated Ti6/4 material and to derive the required S-N curves for the damaged material. This program is described in this section.

1) Test Program

The test program to assess the properties of LSP treated Fan disc material with typical service damages was set-up in accordance with the previous test series to assess properties of the undamaged Fan disc material [8], i.e. same type of test (3-Point-Bend) and specimen geometry were used. Testing was performed at different mean and alternating stress levels representative for the stress levels experienced in service. A total of 59 specimens were used in the program:

- 42 specimens with scratch, representing damaged material
- 14 specimens without scratch, representing undamaged material
- 3 specimens without surface treatment equipped with strain gauges used for calibration purposes

The 14 specimens representing undamaged material were used to check and compare against the original baseline established in [8].

2) Specimens

The specimens were designed such that the maximum principal stress gradient at the notch root matched, as closely as possible, with the stress gradient at the critical location in the dovetail of the Fan disc, derived with FE analysis. The notch root radius was made sufficiently large so that the residual stress field induced by the LSP process was very similar to that expected at the critical disc location.

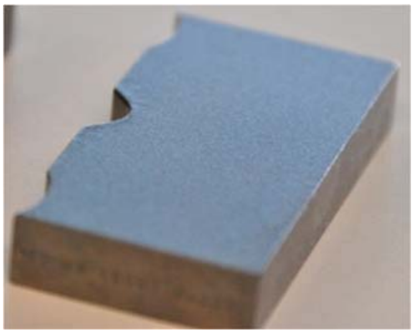

Fig. 7 Specimen

The test specimens were machined from the dovetail area of a production Fan disc. The surface treatment of the test-pieces was carried out in accordance to the fan disc production standard parameters. Most specimens in this program were set-up to represent damaged Fan disc material. An artificial scratch was applied at the notch ground of each of these specimens after the surface treatment to replicate damages found in service.

3) Derivation *of Material Properties*

Testing to failure was performed for different mean stress levels and for each mean stress level the alternating stress was varied. To account for the mean stress level variation the Walker strain parameter [11] was calculated based on:

$$\varepsilon_W = \frac{\sigma_{max}}{E} \cdot \left(\frac{2\cdot\sigma_a}{\sigma_{max}}\right)^m \qquad (1)$$

where: σ_{max} = maximum stress (steady + alternating + residual); $2*\sigma_a$ = total stress range ($\sigma max - \sigma min$); E = elastic modulus; m = empirical fit of the data.

Up to a certain stress level the LSP induced residual stress forces the failure position (crack initiation) to be sub-surface. The Walker strain was therefore evaluated for all points up to a depth of 2 mm into the specimens. The depth exposed to the highest value of Walker strain was considered the most likely failure location. The calculated depths of maximum Walker strain values match well with the failure locations observed on the broken test specimens from testing of undamaged material.

The failure locations for the scratched specimens showed a larger variation between surface and subsurface. Fig. 8 shows

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various failure locations on different specimens.

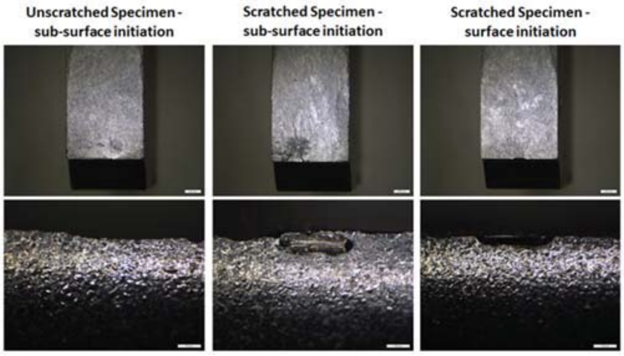

Fig. 8 Specimen failure locations

As the test data have been generated at a range of R ratios, i.e. at different mean and vibratory stress levels, it was useful to collapse the data using the Walker strain approach onto a single curve, i.e. to plot the calculated maximum Walker strain over the number of cycles to failure for each specimen, see Fig. 9. A generic expression for fatigue life can then be derived for any values of sub-surface mean or alternating stress.

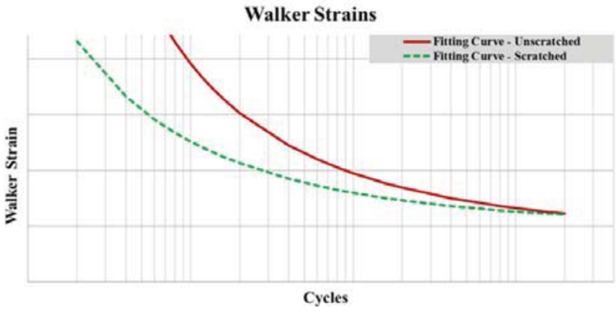

Fig. 9 Walker strain – life relationship

The testing of artificially scratched specimens has shown a drop in strength that reduces and vanishes at lower Walker strains or at higher lives respectively.

The Walker strain – life relationships are used to derive Range-Mean (R-M) diagrams for the selected location on the component, i.e. in this case for the critical LSP treated areas in the Fan disc slots. This can be done in an iterative process, considering the mean, residual and alternating stress gradients at the specific location of the component. The method was developed in [8].

Fig. 10 shows a qualitative example of typical R-M curves for different constant lives (number of cycles to failure).

In addition to the R-M lines of constant life, Fig. 10 also exemplary shows the relationship between mean and alternating stress for two modes. Usually a constant mean stress is assumed for each mode independent from the vibration amplitude. However, non-linear behavior was measured in Fan disc & blade assemblies under certain conditions and is attributed to blade slippage in the slot, depending on the vibration amplitude.

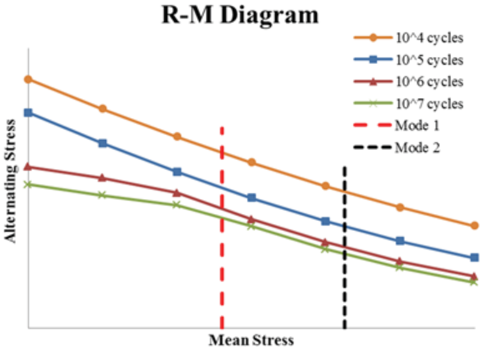

Fig. 10 Example of R-M diagram

An S-N curve for each mode of interest is then derived from the R-M diagram, i.e. from the intersections of the constant life lines and the lines showing the relationship between mean and alternating stress for the specific modes. These S-N lines are specific for a certain disc location and – if applicable – surface treatment as they reflect mean, alternating and residual stress at this specific location.

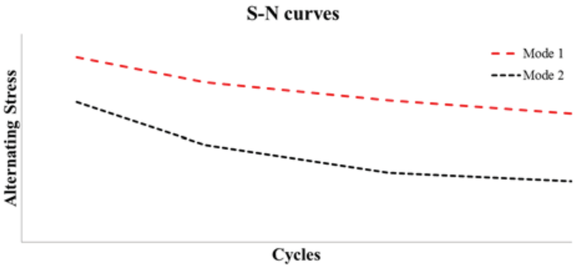

Fig. 11 Example of S-N diagram

IV. RESULT

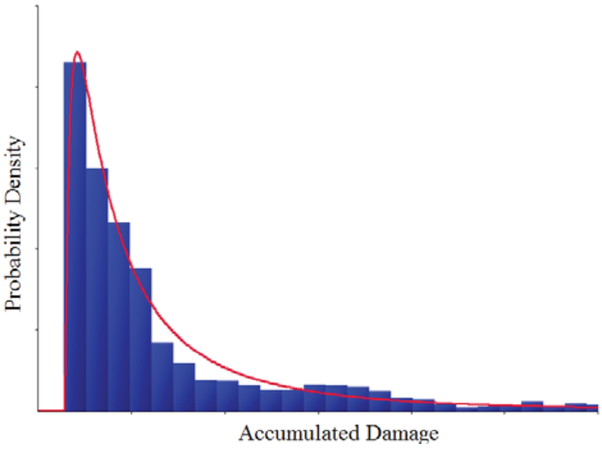

Fig. 12 Accumulated damage with distribution fit

The result of the Monte-Carlo assessment is the accumulated HCF damage for each disc in the analysed fleet (reasonable fleet size, i.e. number of components/engines in service to be selected) for a predefined amount of cycles (usually the declared life of component). The HCF damage probability density function (PDF) is shown in Fig. 12. The accumulated HCF damage is the consequence of the exposure

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to vibration during the service life of a Fan disc, i.e. due to ground operation under cross wind conditions (air framer testing & maintenance procedures, take-offs).

Eventually, the total damage is the sum of the HCF damage and the LCF damage accumulated in the component life. For certification it has to be demonstrated that the probability of crack initiation resulting from service damage during the component life is sufficiently low [10].

V. CONCLUSIONS

The probabilistic damage tolerance methodology presented in this paper has been developed for Titanium Fan discs in aero engines. This is a generic method and can be applied to other components, e.g. to solid fan blades and to future fan blisk designs. However, specific material testing and extensive FE analysis is potentially required.

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