Methods of Modern Lifing Concepts Implemented in On-Board Life Usage Monitoring Systems

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1. ABSTRACT

Modern lifing concepts for fracture critical parts include safe crack initiation life and safe crack propagation life. In military aero engine applications, a portion of the safe crack propagation life is more and more utilised to extend the usage period beyond the limits set by the concept of safe crack initiation life. To really use the benefits of such life extension without reduction of flight safety, it is essential that all engines involved are monitored with respect to individual life consumption. Thus, on-board life usage monitoring systems need to address the crack propagation phase in the same manner as the crack initiation phase.

It is shown how the calculations of fracture mechanics parameters and the resulting crack propagation process are integrated into the algorithms of on-board life usage monitoring software. Applicability of the methods is underlined by results obtained with OLMOS - the on-board life usage monitoring system of the German Tornado fleet.

2. INTRODUCTION

Aero engine fracture critical parts undergo cyclic loading during their operational usage. Due to the nature of this loading, the material experiences fatigue at some highly stressed areas, what leads to initiation and propagation of fatigue cracks.

Fatigue is the life limiting damage mechanism for most of the fracture critical parts, since growth of cracks beyond a certain stage of their development (in other words: beyond a certain crack depth) increases the probability of part failure. In order to maintain the structural integrity of the engine in accordance with the required safety standards, it is necessary to retire a part before an accepted risk level is exceeded. This means that a fracture critical part has got a limited service life.

Fatigue life of a part is defined as a number of cycles (with a given stress range at given temperature conditions) that the life limiting critical area of that part is able to endure until a crack with specified properties has developed.

3. MODERN LIFING CONCEPTS

The classical method to treat fatigue life is the concept of safe crack initiation life (frequently just called: the safe life concept). 'Safe' means in this context that the scatter of material strength is considered and the life of the weakest part of the whole population declared as the life of each member of this population. The consequence of this concept is that only the fewest parts will have generated a small fatigue crack when they all are taken from service. The majority of the parts will be crackfree. And even parts which have developed an initial crack will still have a remarkable portion of remaining life, since in most of the cases the crack can be allowed to grow to some certain crack depth before the engine integrity will be jeopardised.

This behaviour led to the idea to safely utilise some portion of the crack propagation phase. The underlying lifing concept is called the concept of safe crack propagation life. This concept is equivalent to that of the safe crack initiation life, but allows instead of roughly 0.4 mm depth a fatigue crack to grow until some other safety criterion is reached. This criterion is called dysfunction. It includes a number of different cases which all could reduce the structural integrity. Of course - the concept does not accept that the dysfunction condition will be really reached, but provides a well defined safety margin. Due to this real safety margin, the concept of safe crack propagation may be judged as 'safer' than the classical safe (crack initiation) life concept.

In military aero engine applications both these concepts are combined, where the safe crack propagation life is used to extend the initially released crack initiation life.

Another approach - also applicable to military aero engines - is to use the safe crack propagation life alone, thereby ignoring the crack initiation phase. But in this case crack propagation is assumed to start at significantly smaller crack depths (around 0.1 mm). This approach is typically applied for parts made of high strength powder material or for parts of conventional metal if they are loaded beyond the traditional stress levels.

4. SAFE CRACK INITIATION LIFE

The basic idea for the concept of safe crack initiation is that

- a new part is free of defects
- a defect (in this case a fatigue crack) is generated in service
- the part's life is expired, when the defect has been created

The criterion for 'existence' of a crack is that the crack has been initiated and grown to a certain depth. A commonly used value for this crack depth is 0.4 mm. This criterion is a little arbitrary, although sensibly based on long experience.

The safe crack initiation life is established as the number of cycles to reach an accepted statistical probability for the existence of a crack with that depth. The statistical probability takes into account that material strength exhibits some scatter. And for the weakest individuum of the parts' population, the structural integrity must be ensured. Generally accepted statistical probabilities for that weakest part are in the range of 1 out of 750 to 1 out of 1000.

Parts lifed under this concept are not inspected whether the crack is really present when they are retired, and only the fewest of them would contain one. Nevertheless, re-use of the parts beyond the safe life - as defined above - is not considered.

The criterion of this concept - namely the existence of a crack - does not mean that the part will fail immediately when the accepted crack depth is exceeded. Some safety margin to final part failure will remain. However, the concept cannot provide a measure for the real safety of the critical part, since it is unable to predict a value for the failure margin. In most of the applications there will be sufficient margin for a crack to grow to part dysfunction, but it is also possible that the dysfunction life is very close to the crack initiation life. In such very rare cases the crack initiation life cannot be considered as really safe.

5. SAFE CRACK PROPAGATION LIFE

The concept of safe crack propagation life is based on the idea that

- the part contains an initial defect at the beginning of the crack propagation phase (where the defect behaves like a crack of a certain depth)
- the crack propagates under service loading
- the part's life is expired when the crack enters the phase of part dysfunction

Part dysfunction may include a number of different criteria, for example

- unstable crack growth under basic operational loading
- onset of continuous crack propagation due to superimposed vibratory stresses (i.e. if high frequency stress levels exceed the crack growth threshold)
- loss of overspeed capability (i.e. a crack depth where overspeed conditions could cause spontaneous failure)
- unacceptable out-of-balance conditions

In contrast to the crack initiation criterion, the dysfunction criterion really determines the end of the part's life. This enables us to define a measurable safety margin. Thus, the part will be taken from service when a certain portion (e.g. two third) of the number of cycles to dysfunction have been accumulated.

If the concept of safe crack propagation life is used for life extension, the number of cycles to dysfunction encompasses both the crack initiation and the crack propagation phase. The safety factor of two third will then be applied to the total number of cycles.

The safe crack propagation life is established as 2/3 of the number of cycles to reach an accepted statistical probability for the presence of the applicable dysfunction condition. The statistical probability takes into account that material strength and crack growth properties exhibit some scatter. For the weakest individuum of the part's population, the structural integrity must be ensured. Generally accepted statistical probabilities for that weakest part are in the range of 1 out of 750 to 1 out of 1000.

Parts lifed under the safe crack propagation lifing concept are not inspected for cracks when they are retired. Re-use of the parts beyond the safe crack propagation life is not considered, although most of the parts will not contain a crack grown to the depth which is correlated with the dysfunction criterion.

6. PRINCIPLES OF LIFE USAGE MONITORING

Fracture critical parts in aero engines are released only for limited life. They must be retired from service when their life limits are reached. Life usage monitoring activities serve to identify the proper time. How long a critical part can be kept in service, depends on both the released life at the critical areas and their life consumption due to operational usage. Different methods for life usage monitoring have been established.

The traditional method is to count the engine flight time and to multiply it with a cyclic exchange rate. The cyclic exchange rate (also called β-factor) provides a relationship between the flight time and the life consumed at a critical area. But the correlation between flight time and cyclic life consumption is very weak. This means that conservatism needs to be incorporated into the β-factor, what in turn leads to overestimation of life consumption for most of the parts.

In reality, the life consumed during an engine run or flight is based on stresses and temperatures at the critical areas of the components. These parameters depend obviously on the actual mission profiles, engine intake conditions, individual pilot reactions and many other influences. Thus, one can conclude that better exploitation of the released life is achieved with individual monitoring, where life consumption of each part is individually calculated using actually measured engine parameters.

The procedures for individual monitoring consist of effective algorithms for use in real time, able to calculate the consumed life directly from measured engine signals. The algorithms allow for fast transition of the input signals as they appear under real aircraft and engine manoeuvring. Results are available immediately after the end of a flight. Life usage is measured in damage related physical or technical units.

Details of the method have been published at several occasions [1-5]. Here only a summary is given. The method determines the thermal and mechanical boundary conditions for the engine components on the basis of measured time histories of engine operating parameters (such as spool speeds, intake conditions and gas path temperatures and pressures). Based on these boundary conditions, the transient temperature development within the components is calculated. Stresses or strains at critical areas are computed, which are then used together with the corresponding temperature histories to predict the related damage. Critical area damage is accumulated over all engine runs, so to build up complete life consumption records for all monitored parts of an engine.

In order to ensure undisturbed operation of the monitoring algorithms in on-board life usage monitoring systems, the input data are checked for plausibility. Range and rate checks are applied to all input signals. Additional cross checks are performed based on relationships between signals which exhibit sufficient correlation. If data are found faulty, corrective actions are taken trying to restore them. Interpolation of the signal is used over short drop-out periods. If the signal fails for longer periods, substitutes derived from other valid input signals are taken. If no model for signal substitution is available or too many signals fail simultaneously, the life usage monitoring process is stopped and the need for further corrective actions is flagged.

The monitoring results are checked for plausibility at the end of each engine run. If the results are implausible, particularly if faulty input signals have not allowed to complete the monitoring process, an estimate of life consumption is made for the current engine run based on the flight time or - for ground runs - converted engine run time.

The procedures for individual life usage monitoring outlined here (which are basically also applied in the process of determining β-factors for traditional life usage tracking) are closely related to the life prediction process which is part of the entire engine development process. To show how the life usage monitoring algorithms - particularly those parts related to life consumption in the crack propagation regime - are derived from the life prediction process, a short overview over this process is given.

7. LIFE PREDICTION PROCESS

The life prediction process starts from the design mission which is usually defined in the engine specification. The design mission provides the required thrust and power as a function of time. After the engine hardware has been designed, the part geometry and the materials are defined.

In a first step, there are engine performance parameters derived from thrust and power requirements. The performance parameters consist of the temperatures and pressures in the main gas stream, the spool speeds and shaft loads and torque for each point of the design mission. Additionally, the cooling air flows, temperatures and pressures in the secondary air streams are determined.

In a second step, these performance and cooling system parameters are used as boundary conditions for the calculation of transient temperature distributions in the engine components.

The third step is concerned with the mechanical analysis. Total stresses are calculated as sum of centrifugal stresses (due to part rotation), thermal stresses (induced by temperature gradients), stresses from pressures, shaft forces and torque and of assembly stresses. Based on the results of the stress analysis, the critical areas of the engine parts can be identified. Critical areas are those areas which are exposed to the highest stresses and largest stress ranges, and which can be expected to determine the fatigue life of the part.

Finite element programs are employed for temperature and stress analysis. The engine rotor systems, which contain the majority of the fracture critical parts, are of particular interest. Since the rotating parts are mainly axi-symmetric, a 2D analysis is usually sufficient. Disturbances of the axi-symmetry (caused by holes and scallops in flanges, arms and cones) are treated with stress concentration factors. Stress concentration factors are also applied for other areas where the FE mesh might not be fine enough. All load cases of the design mission are investigated.

The stress concentration factors are either taken from text books or determined by a 3D detail analysis. The 3D detail analyses are only performed for a limited number of load cases.

The second and third step together provide stress-temperature histories at the critical areas over the entire design mission. The stress-temperature histories are analysed with respect to their cyclic content. The most damaging cycle is identified and declared as the reference cycle for the considered critical area.

For most of the critical areas, the concept of safe crack initiation life is employed. Under this concept, the number of reference cycles needs to be predicted, which the critical area can undergo until a fatigue crack will have been generated and grown to the predicted depth of 0.4 mm. Material SN-curves are used which describe the relationship between applied stress range and the corresponding number of cycles to crack initiation. Mean stress and temperature effects are covered as well.

For critical areas where the safe crack propagation life concept alone is applied or where the original safe crack initiation life is extended into the safe crack growth regime, additionally the safe crack propagation life needs to be predicted. For this prediction, typically the methods of linear elastic fracture mechanics are used. Two things are required, namely the stress intensity factor range of the most damaging cycle accompanied by R-ratio (which is the ratio of the cycle minimum stress intensity factor to the cycle maximum stress intensity factor) and temperature, and the crack propagation law relevant for the used material. The crack propagation law describes the crack propagation rate as function of the stress intensity factor range, considering also R-ratio and temperature. The accumulating crack growth process is simulated by integration of the crack propagation rate from the initial crack depth to the onset of instability under reference cycle loading. From the number of cycles necessary to propagate the crack up to the dysfunction criterion, one can derive the safe crack propagation life.

8. GEOMETRY FUNCTION

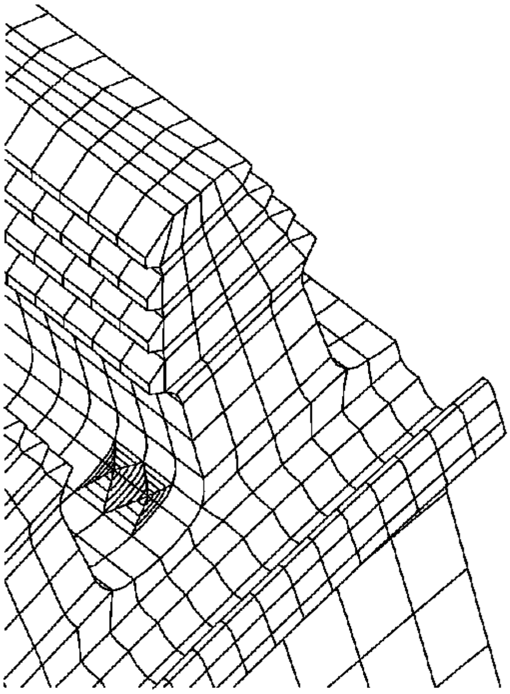
For prediction of the safe crack propagation life and also for life usage monitoring in the crack propagation regime, it is necessary to determine the stress intensity factor. The stress intensity factor depends on the geometry of the component, on the stress field around the critical area, and on the current shape of the crack. As these quantities are very complex, text book solutions for the stress intensity factors are generally not available. Thus, they are calculated by finite element analyses (or on the basis of experimental results, see below).

The crack shape is given by the crack surface (which in many cases may be considered as a plane) and the crack front. It is essential to consider the crack as a whole. In particular, it should be noticed that the stress intensity factor varies along the crack front, so that the crack growth velocity is different at different points of the crack front.

A 3D finite element model is used, where the crack surface and the crack front are introduced. As an example, in Fig 1a,b a modelled crack front at a critical area in the rim slot fillet of a turbine disc is shown. An automated procedure has been developed. Details of this technique were already published in [6-10]. With this procedure, the development of the crack is simulated using finite element calculations in combination with an appropriate crack growth law.

The procedure starts with an initial crack. The initial crack shape is either taken from test experience with real parts or simply assumed as a half or quarter elliptical front at a plane perpendicular to the direction of the maximum principal stress. The exact shape of the initial crack is not so important as the crack will develop into a balanced shape anyway.

For the part containing this initial crack, the stress intensity factor along the crack front is calculated. Typically, the load case belonging to the maximum stress of the reference cycle is used. All relevant loads (as centrifugal and thermal loads) contributing to the stress field around the critical area are included. With the stress intensity factor range and the crack propagation law, the crack growth increment at each point of the crack front is calculated and a new crack shape predicted. Since the crack develops slowly, the stress intensity factor will not change significantly during a small number of cycles. Thus the crack growth for a number of cycles can be computed with the same stress intensity factor distribution. But when the grown crack is distinctly different from the original one, a new stress intensity factor (SIF) calculation becomes necessary. This process (calculation of the SIF, determination of the according crack growth rate and prediction of the new crack shape) is repeated several times building up a complete crack growth history over the number of applied cycles. This crack growth history ranges from an initial crack (which is usually smaller than or equal to that for the crack initiation criterion) to the onset of unstable crack growth.



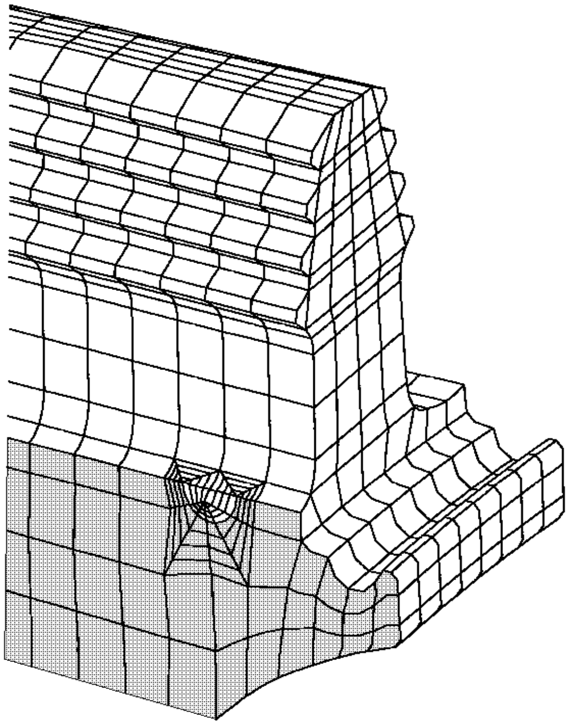


Figure 1: Remeshed FE model of a turbine disc in the vicinity of an introduced crack.

a) View at disc surface

b) View at crack plane

Now, one can choose a path at the crack surface from the point where the crack has originated into the depth of the part, as shown in Fig 2. Along this path the crack depth is measured. For this path, a relationship between the crack depth and the corresponding stress intensity factor can be established. Dividing the stress intensity factor by the stress present at the uncracked critical area itself, defines a so called geometry function. This geometry function provides the relationship between the stress at the critical area and the stress intensity factor at the crack front for each value of the crack depth and enables us to calculate the time history of the stress intensity factor from the time history of the stress at the critical area including the effect of increasing crack depth.

For this procedure it is assumed that the stress fields around the critical area are proportional for all load cases of the mission. In fact, this is not the case. But the error is considered negligible as long as the stress intensity factors for the higher stress levels are modelled correctly. Deviations for sub-cycle stress intensity factor ranges are acceptable as their contribution to the overall damage is small. However, if it turns out that the inaccuracy becomes intolerable, an additional influencing parameter (e.g. the stress gradient) needs to be incorporated into the geometry function.

Currently only a correction for residual stresses is made. The basic idea for this correction is that during the first load cycles some local plastification occurs, what causes some redistribution of the stress fields, as illustrated in Fig 3. After initial plastification, the component is assumed to behave linearly, so that the application of linear elastic fracture mechanics methods appear adequate. This redistribution is accounted for by an additional additive term in the formula for the stress intensity factor calculation.

The just verbally described procedure to determine the geometry function $g(a)$ and the additional additive term $K_{add}(a)$ as a function of the crack depth a is now summarized :

Firstly, a 3D finite element analysis of the uncracked structure under reference load conditions (assumed as extreme load case also in operational usage) is performed, linear-elastically as well as elastic-plastically, in order to determine the linear-elastic stress $\sigma_{elastic,ref}(a)$ and the elastic-plastic stress $\sigma_{plastic,ref}(a)$ along the crack path a. The difference defines the residual stress

$$\sigma_{residual,ref}(a) \;:=\; \sigma_{plastic,ref}(a) \;-\; \sigma_{elastic,ref}(a). \qquad (1)$$

The effective stress $\sigma(a)$ in the uncracked structure can now be formulated as

$$\sigma(a) \;=\; \sigma_{elastic}(a) \;+\; \sigma_{residual,ref}(a)\,, \qquad (2)$$

where $\sigma_{elastic}(a)$ is approximated by the monitored elastic stress $\sigma_{elastic}(0)$ at the critical area ($a=0$), scaled by the respective stresses produced under reference load conditions :

$$\sigma_{elastic}(a) \ := \ \sigma_{elastic}(0) \ \cdot \ \sigma_{elastic,ref}(a) \,/\, \sigma_{elastic,ref}(0) \,. \qquad (3)$$

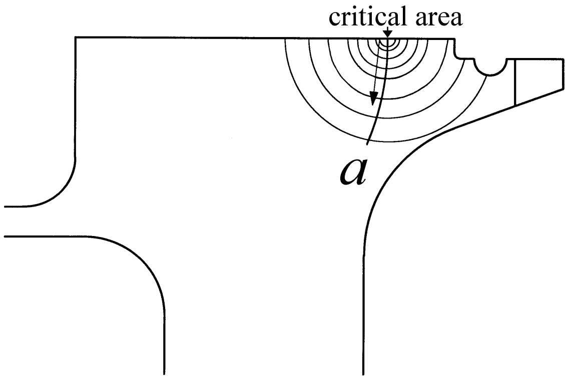


Figure 2: Analysed crack fronts and crack path *a*

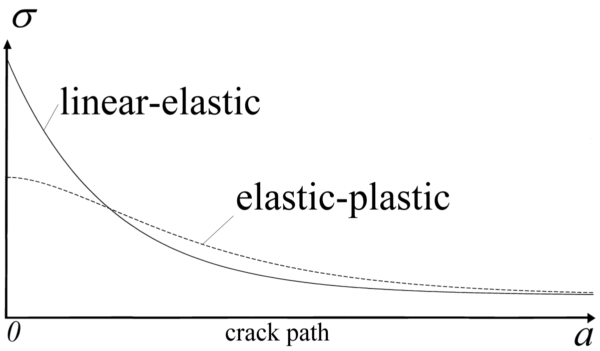


Figure 3: Stress redistribution due to plastification

Secondly, a couple of linear-elastic 3D finite element analyses of the structure containing a crack of different depths *a* according to Fig 1 and Fig 2 is performed, again under reference load conditions, yielding the stress intensity factor $K^*_{ref}(a)$. The stress intensity factor can be represented as the product of the local stress $\sigma_{elastic,ref}(a)$ and a geometry factor $g^*(a)$. Thus, we obtain

$$g^*(a) \ := \ K^*_{ref}(a) \,/\, \sigma_{elastic,ref}(a) \,, \qquad (4)$$

and the stress intensity factor $K(a)$ due to an arbitrary local stress $\sigma(a)$ can be written as

$$K(a) \ = \ \sigma(a) \ \cdot \ g^*(a) \,. \qquad (5)$$

The aim, finally, is to find a representation of $K(a)$ as a function of the known (since monitored) elastic stress $\sigma_{elastic}(0)$ at the critical area (a=0) :

$$K(a) \ = \ g(a) \ \cdot \ \sigma_{elastic}(0) \ + \ K_{add}(a) \,. \qquad (6)$$

This formulation defines the desired geometry function $g(a)$ as well as the additional additive term $K_{add}(a)$ due to residual stresses. After substituting equations (2), (3) and (4) into equation (5), comparison with equation (6) yields

$$g(a) \quad := \ K^*_{ref}(a) \,/\, \sigma_{elastic,ref}(0) \ , \qquad (7)$$

$$K_{add}(a) \ := \ \sigma_{residual,ref}(a) \ \cdot \ K^*_{ref}(a) \,/\, \sigma_{elastic,ref}(a) \ . \qquad (8)$$

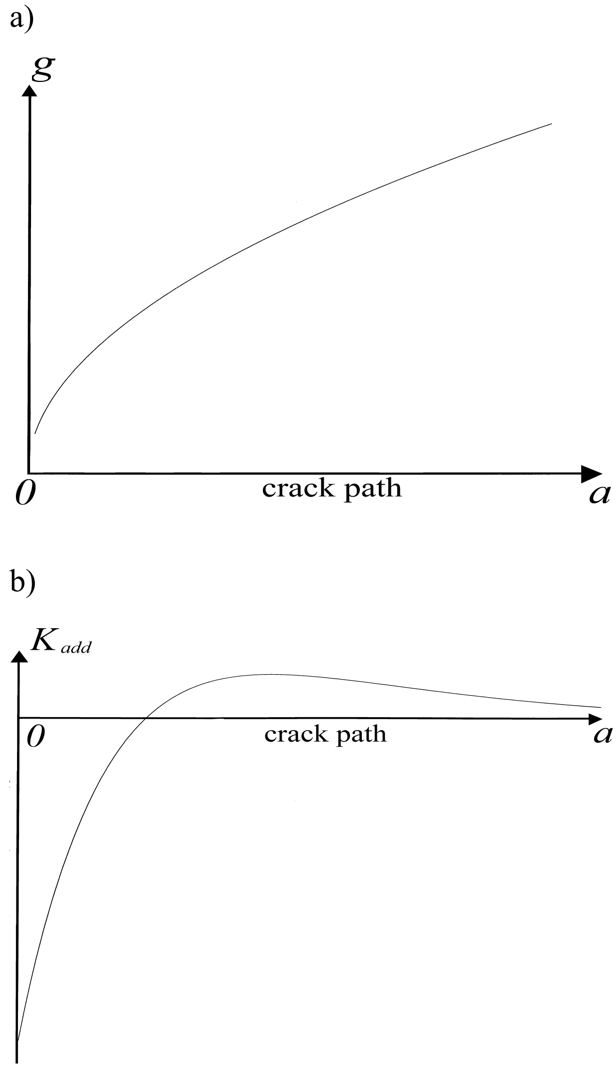


Figure 4: Geometry function *g* and additive term K_{add}

Fig 4 shows a sketch of these quantities as functions of *a*. The geometry function $g(a)$ (Fig 4a) increases usually monotonically with the depth *a*. The additive correction $K_{add}(a)$ (Fig 4b) starts with a negative value at the critical area ($a=0$), increases with increasing depth *a* , and becomes slightly positive. This behaviour of $K_{add}(a)$ is caused by a stress redistribution after plastification as already illustrated in Fig 3. In the chosen example, the highest plastification occurs at the critical area ($a=0$), reducing the stress intensity factor, while - as a static balance - in deeper, not plastified regions the level is greater compared to purely elastic results. Up to what depth values *a* the level of the stress intensity factor is increased depends on the size of the plastified region and on the amount of plastification.

If the geometry function $g(a)$ and the additive term $K_{add}(a)$

shall be used for the prediction of experimental test results rather than for engine monitoring, the quantities occurring in equations (1) to (8) have to be derived under test load conditions. The equations still have the same form, only the index "*ref*" needs to be replaced by "*test*".

There is another way to determine the quantity $K^*_{test}(a)$ which is needed for the evaluation of $g(a)$ and $K_{add}(a)$ in (7) and (8). This way avoids the finite element calculation of the cracked structure and is based on experimental results. It is presumed that for the considered critical area the crack depth a is observed and recorded as a function of accumulated test cycles N. The material's crack growth law and the 3D finite element results $\sigma_{elastic,test}(a)$ and $\sigma_{plastic,test}(a)$ of the uncracked structure must also be known.

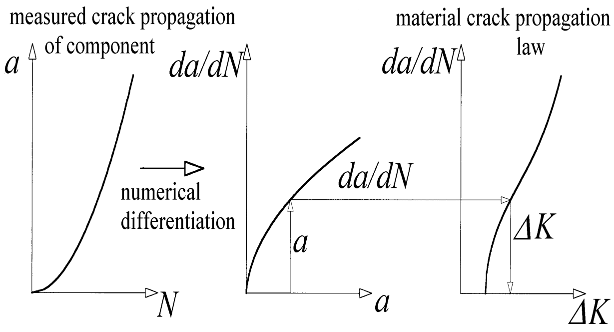


Figure 5: Procedure to determine the geometry function by test results

Fig 5 illustrates the procedure. The crack depth a versus the number of cycles N (left diagram) is differentiated to obtain the crack growth rate da/dN (middle diagram). The crack growth rate can be considered as a function of the crack depth a or as a function of the number of cycles N. Based on the crack growth law (right diagram), one can determine the stress intensity factor range ΔK corresponding to the current crack growth rate da/dN. Thereby, it is assumed that the R-ratio for the stress intensity factor is the same as for the stress cycle at the critical area itself (i.e. at $a=0$). The test evaluation yields the quantity $K(a)=K_{test}(a)$ subject to test load conditions. Using equation (6), written for the test load $\sigma_{elastic}(0)=\sigma_{elastic,test}(0)$, and equations (1),(7) and (8),

$$K^*_{test}(a) = K_{test}(a) \cdot \sigma_{elastic,test}(a) / \sigma_{plastic,test}(a) \tag{9}$$

can be derived, which is needed for the evaluation of $g(a)$ and $K_{add}(a)$ in (7) and (8) where the index "*ref*" is replaced by "*test*".

In case of a dominating elastic behaviour of the structure (only small plastification), the test based evaluation of $K_{test}(a)$ is also applicable for the engine monitoring. In this case $K_{add}(a)$ is negligible, and the geometry factor can be directly obtained from

$$g(a) := K_{test}(a) / \sigma_{elastic,test}(a) . \tag{10}$$

One should be aware that this is an approximation which assumes a proportionality of the stress fields around the critical area between reference and test load conditions which not in all cases can be fully achieved.

The geometry function g - irrespective of the way it has been established - and K_{add} can be interpreted either as a function of the crack depth (as above) or as a function of the number of reference cycles applied. For given reference conditions and a given initial crack depth, there exists a direct correlation between the accumulated number of applied cycles N and the crack depth a (to obtain by integration of the crack propagation law, see lower diagram in Fig 6). This means that both depictions are equivalent. If the geometry function is derived from test results and shall be drawn as a function of cycles, one should be aware that tests are very often performed under overload or with temperatures different from those of the engine reference conditions. Corresponding corrections have to be made.

Nevertheless, for the purpose of life usage monitoring it is preferred to formulate the geometry function as a function of the number of accumulated reference cycles.

9. CRACK PROPAGATION MODEL FOR LIFE USAGE MONITORING

It is the intention that the crack propagation model can be directly integrated into the structure of existing life usage monitoring systems. This can be easily achieved if the life usage monitoring systems are build in a modular architecture.

With such a constellation, only the damage module is concerned, and in this module only the conversion from stress-temperature cycles into the corresponding damage increments. Admittedly, additional input information is required.

Under the concept of crack initiation life, the damage accumulation process is assumed to be a linear process. The damage increments are independent from the current state of accumulated damage and the Miner's Rule is used.

The damage accumulation process in the crack propagation regime - in contrast - is a non-linear one. The damage increment depends additionally on the currently accumulated stage of damage. The physical representation of the accumulated damage is the crack depth, but in the terminology of life usage the number of consumed reference cycles is preferred. The current stage of damage determines on one hand the value of the geometry function and on the other hand the crack growth increment of the reference cycle which is internally used as reference.

If the concept of safe crack propagation life is used to extend the life beyond the safe crack initiation life, then it is necessary that the algorithm switches from one procedure to the other controlled by the current stage of cumulated damage. To distinguish between both procedures, it is checked if the already consumed number of cycles is below or above the released number of cycles to crack initiation. If it is below, then the crack initiation damage process applies, otherwise the crack propagation process.

We know that the life usage monitoring process for aero engines is strongly related to the history of an engine run [1]. In particular, each engine run is treated separately and at its end all cycles are closed and the damage accounts are updated. Since an engine run can be considered as short compared to the life of fracture critical parts and the cracks at critical areas grow slowly, we can assume that the current state of damage is nearly constant during one engine run. This allows us to determine the values of the damage dependent parameters only once per engine run, namely at its beginning.

The functionality can be specified as follows:

- Both the geometry function and the inverse of the reference cycle crack propagation increment (which is the quantity really needed) are given as functions of the accumulated number of cycles. Usually a representation in form of tables is used where the current values are obtained by linear interpolation.
- As part of system and algorithm initiation at the beginning of an engine run, it is checked for the respective critical areas whether the crack propagation regime has been entered. If yes, then the values of the geometry function and the inverse of the reference cycle crack propagation increment are determined. They are kept constant for the whole engine run.
- During the main calculation steps and also within the final calculation, all extracted stress cycles are converted into stress intensity factor cycles using the geometry function. The corresponding crack propagation increments are calculated by evaluation of the crack propagation law according to stress intensity factor range, R-ratio and temperature. Multiplying the respective crack propagation increments with the inverse of the reference cycle crack propagation yields the damage of the considered cycle in terms of the relevant life consumption units (i.e. multiples of reference cycles). Damage increments are accumulated over the whole engine run.
- In the final calculation phase - i.e. after the engine has been switched off - the damage accumulated over this engine run is added to the damage accounts, provided the result checks have been passed.

With this procedure it is ensured that life usage monitoring in the crack propagation phase is completely equivalent to that of the crack initiation regime, and that both lifing concepts can be commonly applied.

10. DETERMINATION OF β-FACTORS

The β-factor (or cyclic exchange rate)

- provides the relation between cyclic life consumption and flight time
- serves to monitor life consumption if there is no on-board monitoring system installed
- serves to fill gaps in life consumption history where the on-board monitoring system is unable to provide correct data

Before defining the β-factor, the relative cyclic damage

$$D_{cycle} := \text{(damage of cycle) / (damage of reference cycle)}$$

is introduced. This ratio is evaluated by different expressions for the crack initiation and the crack propagation phase. Denote the number of cycles to crack initiation with respect to a given stress cycle by N_{cycle} and with respect to the reference cycle (e.g. the main cycle of the design mission) by N_{ref}. For the crack initiation phase, the damage of a cycle is given by $1/N_{cycle}$ and the damage of the reference cycle by $1/N_{ref}$, thus the relative cyclic damage is $D_{cycle} = N_{ref} / N_{cycle}$. For the crack propagation phase, the damage of a cycle is the crack propagation rate $(da/dN)_{cycle}$ and the damage of the reference cycle is $(da/dN)_{ref}$, yielding the relative damage $D_{cycle} = (da/dN)_{cycle} / (da/dN)_{ref}$.

The β-factor is defined as the sum of the cyclic damage D_{cycle} for each stress cycle of a representative number of flights, divided by the accumulated flight time taken in hours :

$$\beta := \Sigma D_{cycle} / \Sigma \text{(hours of flight time)}$$

The β-factor indicates the average damage per flight hour expressed in terms of the number of reference cycles.

The cyclic damage accumulated over all cycles and subcycles of an individual flight can be expected to be higher in the crack propagation regime than in the crack initiation phase. The following effects are expected:

- the main cycle damage is approximately equal to 1 (assuming main cycle similar to reference cycle)
- the subcycle damage in the crack propagation regime is higher due to different slopes of SN curve and crack propagation law
- more damaging subcycles exist in the crack propagation regime since the crack propagation threshold is relatively lower than the endurance limit in the crack initiation phase
- The ratio of cyclic damage of crack initiation to crack propagation strongly depends on the flight mission profile

Considering these effects, one may expect higher scatter in flight to flight damage for the crack propagation phase. In the following, the damage evaluation of the critical area according to Fig 1, performed for a representative number of real flight missions, will show whether the expected effects occur. Before, a description of the procedure is given.

Since the damage for the crack propagation phase is a function of the crack depth a (or, equivalent, of the applied reference cycles N), the cumulated damage is calculated according to the method outlined in section 9 by assuming constant damage over a period of one flight. The necessary auxiliary parameters ($g(a)$, $K_{add}(a)$ and $1/(da/dN)_{ref}$) are updated at the beginning of every flight.

A fast procedure to simulate the damage accumulation of the total component life is illustrated in Fig 6. The upper diagram is the result of a selected number of flight damage calculations for different crack depths (D versus a). The lower diagram shows the relation between crack depth and accumulated damage due to repeated reference cycle loading (a versus N). This relation results from integrating the material crack propagation law. In order to obtain the cumulated damage, these two relations are combined. Starting from an initial crack depth a_0, the upper diagram gives the damage increment per flight D_1 which corresponds to a number of applied reference cycles (N_1-N_0), yielding the new crack depth a_1 by virtue of the lower diagram. Inserting a_1, the upper diagram gives the corresponding flight damage increment D_2, and the iteration process continues.

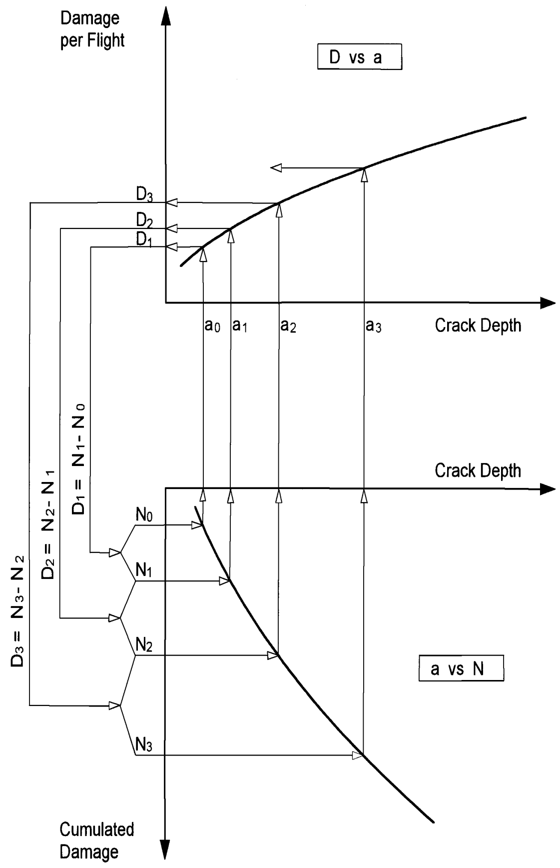


Figure 6: Procedure to simulate the damage accumulation

This procedure was applied to the critical area in the rim slot fillet according to Fig 1 for a representative number of real flight missions. As a result, the crack propagation β-factor β_{prop} turned out to be greater by a factor between 1.5 and 2.0 compared with the crack initiation β-factor β_{init}. This effect was expected (see above). The effect of an increased scatter of the damage between different flights was observed, but turned out to be smaller than expected.

Finally, the question on the benefit gained by the introduction of the safe crack propagation life concept can be treated by comparing the crack initiation life consumption with the crack propagation life consumption over a representative number of flight missions.

To quantify the benefit due to the extension of the safe crack initiation life concept to the safe crack propagation life, we refer to the introduction of the 2/3 dysfunction life (cf. section 5) which is equal to 2/3 of the number of reference cycles up to the dysfunction criterion (e.g. unstable crack growth), including crack initiation and propagation phase. Let N_{init} and N_{prop} be the number of cycles in the respective phase. If we divide these numbers by the respective β-factor β_{init} or β_{prop}, the respective life times in flight hours are obtained. Thus, we are able to compare the flight hours in the crack propagation phase with those in the crack initiation phase. The ratio yields a measure for the benefit gained by the inclusion of the crack propagation regime.

In the example shown in Fig 1 (rim slot fillet of a turbine disc) the service period in terms of engine flying hours can be increased by about 40% (corresponding to $\beta_{prop} / \beta_{init} = 2$), if in addition to the crack initiation regime a safe percentage of the crack propagation regime is utilised.

11. CONCLUSION

Algorithms to monitor life consumption in the crack propagation regime have been developed. They are formulated in such a way that they are compatible with already implemented formulas for crack initiation monitoring, in particular they are also formulated on the basis of reference cycles rather than on crack dimensions. The example of a critical area in the rim slot fillet of a turbine disc shows that the service period in terms of engine flying hours can be increased by about 40% if in addition to the crack initiation regime a safe percentage of the crack propagation regime is utilised.

12. REFERENCES

1. Broede, J., "Engine Life Consumption Monitoring Program for RB199 Integrated in the On-Board Life Monitoring System", AGARD CP 448, Quebec 1988, Paper 9.
2. Broede, J. and Pfoertner, H., "Advanced Algorithm Design and Implementation in On-Board Microprocessor Systems for Engine Life Usage Monitoring", 15th Symposium AIMS, Aachen 1989, DLR-Mitt. 90-04,1990.
3. Dhondt, G. and Möhres, W., "Modelling the Engine Temperature Distribution between Shut Down and Restart for Life Usage Monitoring", 16th Symposium AIMS, Munich 1991, DLR-Mitt. 92-01, 1992.
4. Pfoertner, H. and Roß, C., "Preparing Life Usage Monitoring for the Next Decade", 18th International Symposium AIMS, Stuttgart 1995.
5. Broede, J. and Pfoertner, H., "OLMOS in GAF MRCA Tornado - 10 Years of Experience with On-Board Life Usage Monitoring", 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Seattle, WA 1997.
6. Dhondt, G., "Zyklische Mode-I Rissfortschrittsberech-nungen mit ABAQUS", Proceedings of the German ABAQUS User's Conference, Innsbruck, Sept. 1997, pp 1-17.
7. Dhondt, G., "Zyklische Mode-I Rissfortschrittsberech-nungen in Komplexen Bauteilen mit der Finite-Elemente-Methode", Proceedings of the DGLR Jahrestagung, Munich, 14-17 October 1997, pp 381-390.
8. Dhondt, G., "Automatic 3-D Mode I Crack Propagation Calculations with Finite Elements", Int. J. Num. Meth. Engng., *41*, 1998, pp 739-757.
9. Dhondt, G., "Cutting of a 3-D Finite Element Mesh for Automatic Mode I Crack Propagation Calculations", *to appear in* Int. J. Num. Meth. Engng., 1998.
10. Dhondt., G., "Automatic Three-Dimensional Cyclic Crack Propagation Predictions with Finite Elements at the Design Stage of an Aircraft Engine", *to appear in* the Proceedings of the "Applied Vehicle Technology Panel Symposium on Design Principles and Methods For Aircraft Gas Turbine Engines" of the RTO, Toulouse, France, 11-15 May 1998, Paper 33.