Component Life Analysis

The papers in this section are from two sessions. The first session was chaired by Charles F. Tiffany, and the second session, by Joseph P. Gallagher.

Gas Turbine Engine Disk Cyclic Life Prediction

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Major disk design criteria are identified with emphasis on the life limiting design and the application of life prediction techniques. Design for low-cycle fatigue (LCF) capability includes consideration of operator usage, material characteristics, temperature, and stress analysis. Analytical stress analysis methods are discussed and related to experimental testing of both specimen and full-scale components. The role of initiation time in the total component life is discussed with emphasis given to analytical techniques, including finite element, finite difference, and the role of stress concentrations on fatigue life. The fatigue life initiation system and its inter-relationship with the flight profile including the effects of time, temperature, stress, and material characteristics are highlighted. Attention is focused on the role of crack propagation in the disk design system including the design of disks for internal defects. The general role of fatigue crack propagation and subcritical flaw growth is highlighted along with the inter-relationship with nondestructive inspection techniques for surface and sub-surface defects. The future of initiation-propagation relationship to total disk life concept is explored in light of improved NDI, advanced fracture mechanics analysis, and the potential for disk retirement for cause.

Introduction

MAJOR gas turbine engine disks are some of the most highly stressed components in the engine. The rotational kinetic energy in a typical stage can be of the order of 15 $\times 10^6$ in.-lb. For a high by-pass ratio engine of the size of the JT9D (takeoff thrust equal to 53,000 lb) the fan disk has a centrifugal load at the rim equal to the thrust of over 100 JT9D size engines. It is, therefore, imperative that well-calibrated analysis and life prediction of these components be made with the most up-to-date analytical and experimental techniques available. This paper provides an over view of the low cycle fatigue life prediction system as it is applied to major rotating components such as disks. It discusses the various ingredients that go into such a life prediction system including the temperature and stress analysis, generation of life curves, fracture mechanics, and the experimental calibration that is carried out.

In the final design of disks, four major design criteria must be considered: 1) dimensional change in the disk, 2) prevention of disk rupture, 3) high-frequency fatigue which includes resonance, flutter, and buffeting, and 4) low-cycle fatigue. Of these four considerations, only the low cycle fatigue life of the disk under the environment that it would operate over its lifetime will be discussed in this paper.

Definition of Life and Cycle

Before any detailed discussion of the life prediction system can be made, it is essential that the term "life" be defined. At Pratt & Whitney Aircraft, "life" is defined as the number of cycles to a $\frac{1}{32}$-in. long crack on the surface to a probability of 1:1000. When applied to a disk certified for 15,000 cycles, it means that out of 1000 disks of a given design, one disk will develop a $\frac{1}{32}$-in. surface crack at 15,000 cycles. The significance of a $\frac{1}{32}$ in. crack is that the inspection capabilities of both the military and commercial operators can easily detect a crack of $\frac{1}{32}$ in. At this stage it might be worthwhile talking about crack initiation and crack propagation. Initiation of a crack could be defined down to a very small crack length. However, for the sake of simplicity we consider life to a $\frac{1}{32}$ in. crack as initiation life. The crack propagation life from $\frac{1}{32}$ in. to rupture is dependent upon many things such as the geometry, material, environment, and the vibratory stress (high cycle fatigue) which the disk experiences. It is, therefore, a very complex subject and more work needs to be done before the life of the disks can be extended to crack lengths beyond $\frac{1}{32}$ in. by fracture mechanics. It should be emphasized that whereas low vibratory stresses may not be that significant during the crack initiation stage of the life, they can be extremely critical for some geometries and materials during the crack propagation phase. A crack could be initiated by low cycle fatigue and rapidly propagate in high cycle fatigue if for the vibratory stress existing in that disk, the stress intensity value is greater than the threshold stress intensity value for that material. In the bore of the disk where vibratory stresses are low, a fracture mechanics design system has been developed for internal defects and is currently used. More discussion of the fracture mechanics aspects of disk design are given later in the paper.

Before we go into the details of the life prediction system, a few words should also be said about the definition of the cycle. For a simple transport type of application, a cycle could be defined as the stress history from the time of take-off to landing. Even in such a simple stress history there could be sub-cycles of stress which occur because of the thermal response of the disk as it goes through take-off, climb, cruise, descent, and landing. Additionally,

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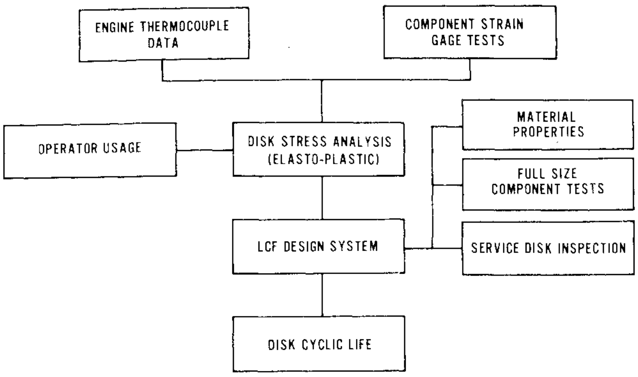

Fig. 1 Disk LCF design system.

there could be a stress sub-cycle due to the application of thrust reversers. However, for most cases the effect of these sub-cycles is not significant. Wherever significant, sub-cycles are accounted for. For a military type of application, the cycle can be extremely complex. A military aircraft may be expected to perform different types of missions such as training, high and low altitude navigation, weapon delivery, etc. Each of these missions could involve large changes of stress and temperature throughout the flight and their cumulative damage effects have to be considered. For a military aircraft it might make more sense to talk about the life of the disk in terms of numbers of hours rather than cycles where it is assumed that we know ahead of time the types of missions and the proportion of time during which each of these missions will be flown. Low cycle fatigue cumulative damage is done in the linear manner, Miner's[1] law for cumulative damage, because of the simplicity of this approach and because other rules have not been universally applicable to all materials at all stress levels. An extensive test program for different materials and variety of mixed loading conditions was conducted to evaluate various cumulative damage hypothesis including those proposed by Wilkens,[2] Manson,[3] Freudenthal,[4] Corten and Dolan.[5] The conclusion was that none of these rules offered any significant advantage over Miner's simple rule.

Life Prediction System

The prediction of LCF crack initiation life follows the steps outlined in Fig. 1. This includes performance definition, thermal analysis, stress analysis including detailed finite element stress analysis of stress concentration features, and finally reading the life from fatigue life curves.

Basic performance parameters of rotor speeds, pressures, and temperatures at each station along the flowpath, as well as engine, fan, and cooling airflows are calculated for each operating condition along the flight. These operating conditions generally include idle, takeoff, climb, cruise, and descent. Taking these basic performance parameters, the compressor and turbine component aerodynamic characteristics are analyzed to give a breakdown in stage by stage temperature and pressure levels. In addition to this nominal performance information, additional rotor speed, and temperature increments are provided to account for production tolerance, field trim, and field deterioration effects. This results in a life prediction for the worst performing production engine after it has been flown. This performance information provides the boundary conditions for the thermal analysis of each disk.

Thermal Analysis

The transient thermal analysis is provided through the use of a three-dimensional transient finite difference computer solution encompassing convection, conduction, and radiation heating effects. The environmental conditions surrounding the disk are defined as previously discussed, from the performance parameters as a function of time throughout the flight cycle. Boundary thermal and heat transfer coefficients are defined based on previous engine and rig experience. The transient temperatures are calculated using this information by making use of an implicit solution technique which incorporates a dynamic time step expander and contractor which assures that the transient time step is small enough to insure accuracy, but as large as possible to conserve computer time. Finally, the temperature calculations are arranged and stored on magnetic tape with the format for direct input to the disk stress analysis.

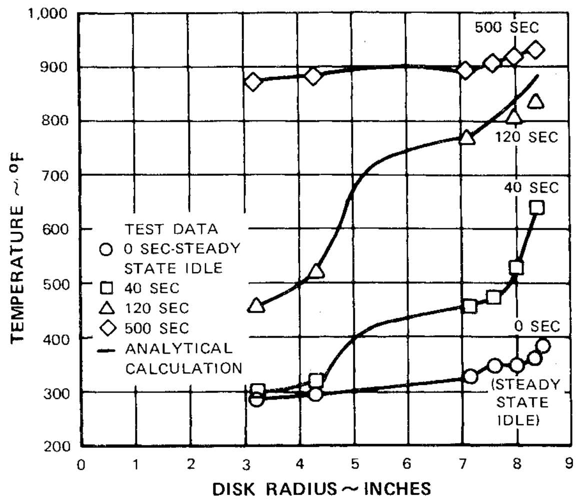

Fig. 2 Turbine disk temperature data match.

The thermal analysis makes use of rig and engine temperature measurements to determine critical heat transfer and cooling air temperature boundary conditions. This testing requires extensive thermocoupling of rotors including several thermocouples located radially along each disk profile. Figure 2 shows a typical temperature distribution prediction compared with test data.

Stress Analysis

Disk analysis now combines the temperature distribution just discussed with the centrifugal loading by means of a finite difference stress analysis technique. Since LCF life is sensitive to cyclic strain levels, particular care must be taken to insure that all loading is included, plastic stress redistribution is accounted for, and local stress concentrations are evaluated.

The elastic-plastic stress analysis program is based on a finite difference representation of a series of connected, concentric rings of variable width and thickness. The plastic capability is achieved by iteration from an initial elastic solution, bringing each ring to its proper location on the material stress-strain curve. The iteration procedure is generally convergent for practically all time points in the flight cycle history because of the constrained nature of disk bore plasticity. The elastic-plastic program also includes simple shell elements that can be used to compute radial disk loads introduced by the radial incompatibility of disk and the appendages.

The elastic-plastic stress analysis program is the heart of routine disk stress analysis. The program is extremely rapid, allowing for a detailed study of the disk flight cycle response. Figure 3 illustrates the excellent correlation between predicted strain level vs engine speed for a typical spin pit test.

Good design practice requires that the various attaching

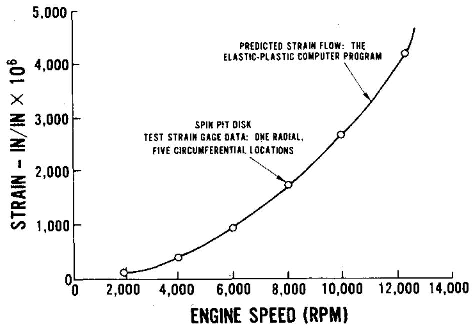

Fig. 3 Comparison of predicted and measured disk strain levels—experimental compressor disk.

hardware result in a minimum net bending of the disk. Unfortunately, this is not always achieved, and therefore, the effects of bending must be included. A rather complex computer program has been developed which provides analyses for every time point along the flight cycle with a minimum of engineering effort. The result of this analysis is a definition of nominal stresses and deflection along the disk profile for the full mission.

In addition to calculation of nominal stresses, local stress concentrations must be evaluated. Bolt holes are analyzed for stress concentrations under the biaxial stress field as a part of the basic computer system. Blade attachment slots are not quite as simple. Stress concentrations must be calculated in the base of the dovetail and fir tree attachments. Standard attachment slots have been modeled to provide a system of calculating the stress concentration without requiring a detailed finite element analysis. In many instances a reduced stress concentration is required and a finite element or integral equation analysis is employed to determine the optimum slot profile. Such design techniques as elliptical shaped slot bottoms and optimum fillet radii are utilized to minimize the stress concentration.

The finite element program utilizes general quadrilateral plate or axisymmetric elements, assembled from constant strain triangles. The program is written such that a disk structure may be modelled using combined plate and axisymmetrical elements; the plate elements are used to model rim areas. The program has the capability to model blade-rim interactions including nonuniform blade loading. It interpolates the necessary thermal data and rotational speeds from the data bank to account for the body

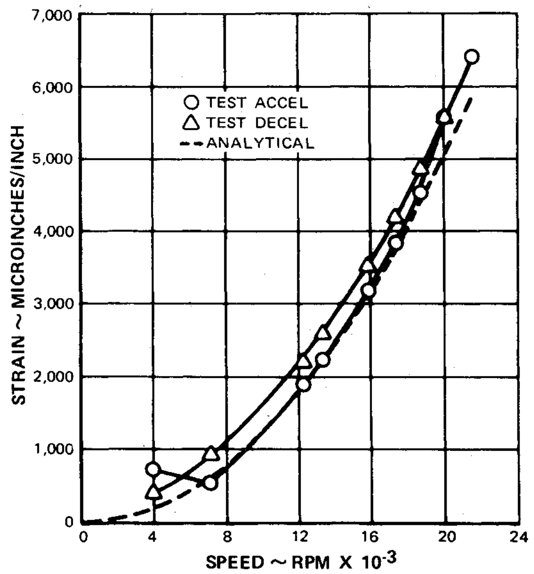

Fig. 4 Correlation of strain gage and analysis data—compressor stage dovetail slot.

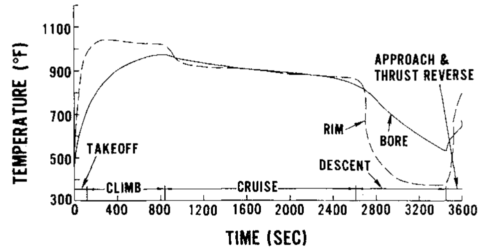

Fig. 5 Typical disk bore and rim temperature response.

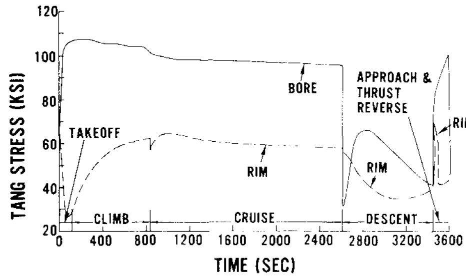

Fig. 6 Typical turbine disk bore and rim stress response.

forces. Other major features of the finite element program include automatic mesh generator and full plotting of stress, strain, temperature, and deformed geometry data, including numerical and contour plots. An example of the good correlation between the finite element analysis and spin pit strain gaged data for a blade attachment location is shown in Fig. 4.

A typical example of the thermal and stress response of a turbine disk is shown over a full flight for a transport engine in Figs. 5 and 6. It indicates the existence of small sub-cycles at the bore during descent and at both the bore and the rim during thrust reverse. Similar analysis is performed at other location of the disk such as bolt holes and snaps. This type of flight cycle analysis is fully automated utilizing thermal and stress analysis tools described previously and directly accesses the material life properties data base.

Definition of Life Curves

Extensive testing of specimens for many materials has shown that for a given temperature, life is dependent upon two important parameters, namely, the cyclic strain range and the mean stress. Before life curves, as shown in Fig. 7, can be drawn, a statistically determined number of specimens have to be run and the shape of the life curves determined from these data. These curves are then adjusted by the results of cyclic tests run on full scale com-

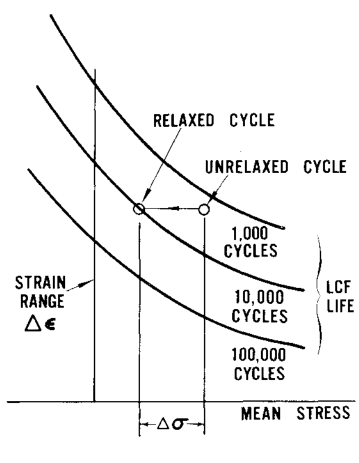

Fig. 7 Life curves.

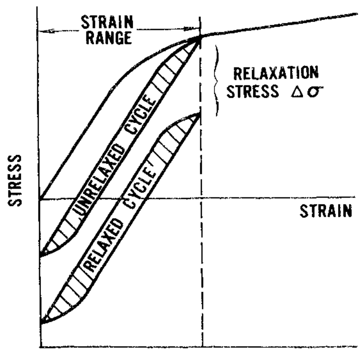

Fig. 8 Effect of relaxation on mean stress.

ponents in the ferris wheels (large static load rigs), spin pit, and in some cases, experimental engine endurance tests. Additionally, information from the field is continually obtained by requesting a statistically determined number of samples from the operators close to the full certified life of the disk. These disks are then examined to determine the existence of sub-1/32-in. cracks. Some of these disks are also cycled in the ferris wheel to determine the remaining number of cycles to 1/32 in. and higher length cracks. This information, which over the last 15 years has been an important ingredient of our low cycle fatigue design system, is fed into the loop to calibrate the prediction with the actual field experience.

Let us now examine an important effect, that is the effect of time at load and temperature on life. Figure 8 shows the stress behavior over one full cycle of a disk at a given location. This location is near a stress concentration such as bolt hole or a blade retention slot. In a gross sense the disk is an elastic body, even though locally at the stress concentrations the disk does experience cyclic stresses and strains significantly beyond the proportional limit. The small volume of material near the stress concentrations experiences a cyclic strain range. Initially, the hysteresis loop is as shown in Fig. 8. Over a period of time this volume of material, experiencing a strain controlled type of cycle, relaxes its stress, and the hysteresis loop drifts down to the value as shown in the figure. As we had said earlier, the life of the disk is strongly dependent upon the cyclic strain range which does not change over the life of the disk for that type of cycle and on the level of mean stress which does change due to relaxation and which can have a significant effect on life. A vast number of specimens for different materials, full scale component tests, and behavior of disks in engines in the field have substantiated this phenomena. For a given type of mission, associated stress, temperature, and time history the design system not only calculates the conventional unrelaxed life, but also determines the effects of stress relaxation near the stress concentration. For some designs and thermal conditions this effect could be deleterious rather than resulting in increased life. For some turbine disks the major portion of the cyclic stress is on the compressive side due to large thermal gradients. Under those circumstances, because of negative relaxation, the hysteresis loop would drift upwards resulting in increased mean stress and thus reduced low cycle fatigue life.

Correlation With Experience

Proof of any design system is its performance in the real world. Generally speaking our life prediction system has correlated very well with the field, considering that Pratt & Whitney engines accumulate in excess of 30 million hours of flying time every year in the commercial airlines alone. This experience has provided us with a large statistical base. As stated earlier we have continuous inspection programs of disks by recalling disks close to their certified lives. Figure 9 shows the results of some of these programs.

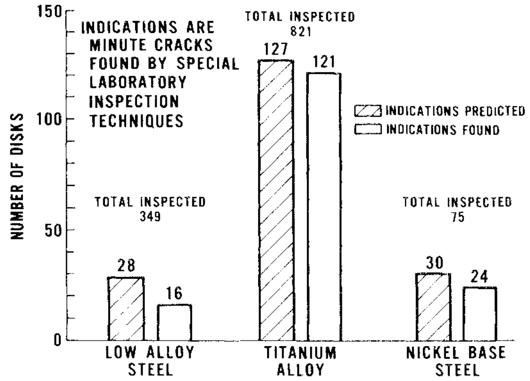

Fig. 9 Comparison of predicted vs observed cracks.

It shows for steels, titanium, and nickel base alloys the total number of disks inspected, the number of disks predicted by our system to have sub-1/32-in. crack, and the actual number of disks with such indications. The agreement is very good. This is not to say that there have not been problems in the field. But most of these problems have been associated with material defects or the high vibratory stress in some designs. Continuous efforts are being made in stress, temperature, and fracture mechanics analysis to improve our design system.

Statistical Analysis

Fatigue is a highly statistical phenomenon exhibiting large scatter on life for a given stress and temperature environment. No LCF life prediction system can be complete without a good understanding and application of the latest statistical techniques. Extensive statistical analysis is used in analyzing test data as well as calibration of the life prediction system using field experience. In applying statistics to test data, a basic Weibull analysis is used. This enables the scatter of the fatigue life to be clearly presented allowing evaluation of the data for consistency as well as determining a suitable minimum failure rate life. Figure 10 gives a typical example of LCF life to 1/32-in. crack. As can be seen, the data are best fit by a curved line which we have found is characteristic of all materials used in disks. The failure rate of 1/1000 is used for life to 1/32 in. crack length.

Analysis of field data to calibrate the life prediction system with field experience makes use of an internally developed statistical tool called Weibest analysis which combines both field inspection data giving number of

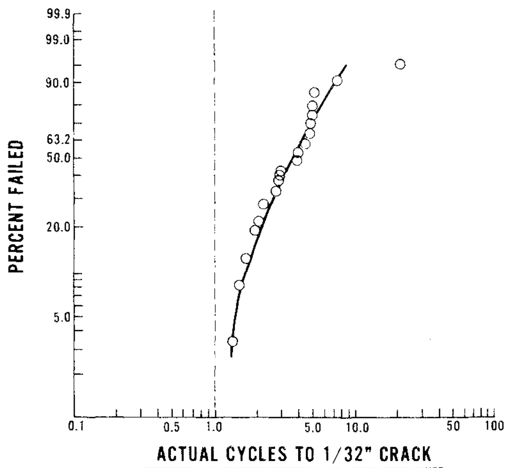

Fig. 10 Statistical variation of life.

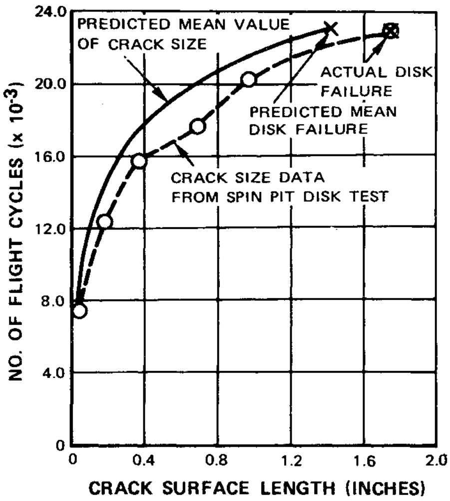

Fig. 11 Correlation of crack progression analysis with test.

parts cracked as well as those parts inspected which have not cracked. Again the design system is calibrated to a 1/1000 failure rate.

Fracture analysis makes use of statistical theory in another way. The description of defects in the material is determined from suitable inspection procedures. The variability of crack progression rate is defined and characterized. These two effects are then combined with a Monte Carlo type statistical analysis to predict crack progression.

Fracture Mechanics

Over the last five years fracture mechanics has become a viable ingredient of our LCF design system. Previous to that time fracture mechanics as a tool was more widely used to understand and solve existing field problems and less as a part of the design system. When fully developed and calibrated the fracture mechanics design system can aid the designer in choosing optimum materials, setting allowable stress levels and selecting nondestructive inspection standards. The fracture mechanics is a discipline which, for a given structure and its operating environment and loads, determines the cyclic dependent growth of a crack from a given initial size to rupture. This crack growth is a strong function of local stress variation, spectrum of loading, temperature, and material properties.

The fracture mechanics analysis for predicting crack growth in disks under flight cycle loading can be broken

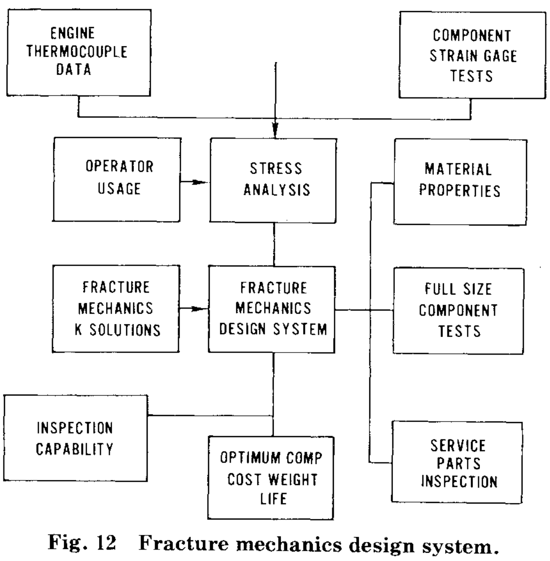

Fig. 12 Fracture mechanics design system.

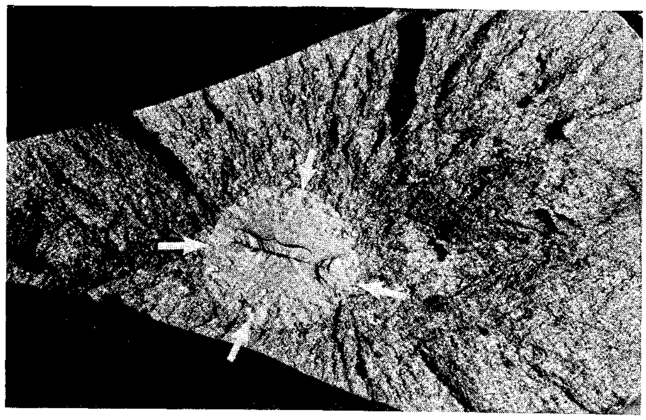

Fig. 13 Example of fracture originating from flaw.

into two classes of problems, growth of a subsurface crack from an inherent material defect which is assumed to behave as a crack and cyclic growth of a surface crack initiated by LCF loading of unflawed material as described in the previous discussion. In both cases of crack growth, the elastic fracture mechanics correlation of the crack growth rate *(da/dn)* and the crack-tip stress intensity factor (ΔK) which is a parameter that combines the crack length and the local stress is numerically integrated to determine crack size as a function of the number of cycles. An example of actual hardware correlation is shown in Fig. 11.

The total fracture mechanics life prediction system requires many of the ingredients necessary for a conventional LCF design system. The flow chart of such a system is shown in Fig. 12. The three key ingredients for an adequate fracture mechanics analysis are; stress analysis which requires a full understanding of the mission profile and the operating thermal and centrifugal environment of the component; fracture mechanics stress intensity K solutions which are a function of disk geometry and stress; and the material properties definition over a range of temperatures including the cyclic crack growth rate, K_{IC} (toughness) and threshold stress intensity factor which is the fracture mechanics equivalent of the conventional endurance limit. The flight cycle for the engine disk is analyzed in the same manner as has been described to determine the cyclic stress history and mean stress levels at each specified disk location. The actual sequence of these cycles is tracked during the computer simulation of crack growth.

Subsurface Material Defects

The first class of problems associated with fracture mechanics is the problem of subsurface crack growth from inherent material defects. A review of aircraft gas turbine history points out several titanium and steel disks which have ruptured due to cyclic crack growth from an internal material defect. An example of such a failure is shown in Fig. 13. This disk which was manufactured from air melted AMS 6304 steel, accumulated about 10,000 cycles and was in the field for about ten years before it ruptured due to the cyclic growth of the crack from the initial material defect reaching a critical crack length. The light circular area is the zone of LCF crack propagation followed by a rapid tensile failure. The processing of both the steels which are now vacuum melted and the titanium alloys used in aircraft gas turbines now include stringent controls which minimize the occurrence and size of these defects. In addition, we apply fracture mechanics as a part of our design procedure to prevent failures from material defects in these alloys. This design system is tied to the material properties as well as the NDI standards. As stated earlier the disk bore experiences very low vibratory stresses and hence the application of fracture mechanics to this area is relatively simple.

The subsurface crack growth analysis is based on the material defect that could be missed by NDI, local cyclic and mean stress levels, temperature, and necessary material properties. The subsurface crack stress intensity factor is computed from theoretical solutions for a buried flaw, circular in shape, and oriented transverse to the maximum normal stress component. The subsurface crack size has a statistical variation which may be truncated for cracks larger than a specified minimum inspection standard; the material parameters are also fit to statistical functions to account for the variability. The fracture mechanics life (cycles to grow a crack to the critical crack size) is obtained by a computer program which combines the statistics of flaw size and material properties, and integrates the actual load cycle history. The resulting life is based on a specified level of the probability of occurrence in a given number of disks.

Surface Crack Propagation

For an LCF initiated crack, the second class of problems to be solved by fracture mechanics, the total life to rupture is calculated by combining the features of fracture mechanics analysis and the crack initiation analysis previously discussed. The major difference between the surface crack and the subsurface crack problems is the evaluation of the crack-tip stress intensity factors. The stress intensity factor for the surface crack is evaluated for different geometries depending upon the details of the stress field local to the notch. These stress intensity factors can be computed using the two or three-dimensional integral equation techniques. The crack initiation and propagation are treated as independent statistical variables in a Monte Carlo type of analysis which predicts the total life to rupture. As stated earlier, since the prediction of a crack growth from $\frac{1}{32}$ in. is a complex problem due to the effect of high cyclic fatigue resulting from the vibratory stresses, we still limit the life of the disk to $\frac{1}{32}$-in. crack. As our understanding of fracture mechanics and our ability to predict vibratory stresses in disks improves, we will be able to utilize the available life of the disks to a greater degree.

Retirement of Disks for Cause

The discussion of fracture mechanics naturally leads into the concept of retiring disks for cause rather than retiring disks when they reach a statistical minimum calculated life as is done presently. This concept can be made possible by the application of fracture mechanics and by significant improvements in the reliability and resolution of nondestructive inspection techniques. The retirement of disks for cause means that disks would be inspected at inspection intervals determined by fracture mechanics and the available NDI methods and would be put back into the field if they passed the inspection with practically no limits on the number of times this could be done. This process would utilize the lives of those disks which are not close to the statistical minimum. Figure 10 shows a statistical distribution of disk lives vs the number of cycles. As stated earlier, the disk lives are presently set to a probability of $\frac{1}{1000}$. Since it is not possible to know which disks are close to the minimum and because the NDI capabilities have not yet reached the desired reliability and resolution, all disks of that design have to be retired at the statistical minimum life. Examination of Fig. 10 indicates that a large number of disks have life significantly greater than the minimum. For example, greater than 50% of the disks have lives in excess of three times the minimum. It is our hope that improvements in fracture mechanics design systems which are being actively pursued and significant improvements in NDI will make retirement of disks for cause with its obviously large payoffs possible.

Summary

This paper has presented an overview of the disk design system used at Pratt & Whitney Aircraft. We have outlined the development of the design system which represents a significant effort over the past 15 years culminating in a two-pronged life prediction system. Disk crack initiation life prediction has been outlined as well as the analysis techniques used to predict crack progression. The role of internal defects in setting allowable disk stresses has been outlined including a discussion of surface crack growth. Finally, the application of statistical analysis to life analysis has been discussed pointing out the important role statistics plays. Future work is planned to extend fracture mechanics analysis to include the effects of vibratory stresses and pursue the retirement of disks for cause.

References

[1]Miner, M. A., "Cumulative Damage Fatigue," *ASME Transactions: Journal of Applied Mechanics*, Vol. 12, Sept. 1945, pp. A159–A164.

[2]Wilkins, E. C., "Cumulative Damage in Fatigue," *Proceedings of the Colloquiam on Fatigue*, May 1955, pp. 321–331.

[3]Manson, S. S., Freche, J. C., and Ensign, C. R., "Application of a Double Linear Damage Rule to Cumulative Fatigue," TMX-52226, June 1966, NASA.

[4]Freudenthal, A. M., "Accumulation of Fatigue Damage, " *Proceedings of the International Conference on Fatigue on Aircraft Structures*, Academic Press, New York, 1956, pp. 146–177.

[5]Corten, H. T. and Dolan, T. J., "Cumulation Damage Fatigue," *Proceedings of the International Conference of Metals*, Vol. 1, London, 1956, Institute of Mechanical Engineers.