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IMPACT OF ENGINE OPERATION ON GAS TURBINE COMPONENT DURABILITY USING DUCTILITY EXHAUSTION

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ABSTRACT

Components in the hot section of a Gas turbine experience both cyclic and hold time loading at high temperatures as the engine is subjected to starts, changes in load, dwells and shut down. These loading profiles can lead to damage from both fatigue and creep and can also lead to the interaction of these two damage mechanisms over the duration of the service interval. Accurate prediction of the accumulation of this damage is critical to managing the engine and avoiding unplanned down time and cost over the operational period. This paper presents an approach to predict the combined effects of creep and fatigue damage using ductility exhaustion. The approach, which has been expanded to include Superalloys, predicts how damage accumulates over the load cycle and how those cycles can cause interaction between the damage mechanisms. It is imperative this behavior is understood for accurate life prediction and optimal engine management.

INTRODUCTION

Operators of land based gas turbines are dependent on the availability of their engines for the continued operation of their business. Unplanned down time is costly, disruptive and represents a significant risk to their business. Reliability is therefore of utmost importance and from an OEM perspective is a critical aspect of satisfying customer expectations and needs. Reliability covers a range of potential issues, not least material degradation due to creep and fatigue damage. Other issues (such as vibration etc.) can result in engine shut down; however, it is the potential for catastrophic failure from compromised materials that presents a significant risk to safe and reliable operation. It is for this reason that OEMs expend significant effort in developing tools and methodologies to predict damage in these components due to general operation.

Finding the correct approach that delivers a balance between accuracy and practicality is the challenge; in particular, models that confidently predict long term creep damage. Practical considerations, such as time, create specific challenges when building long term material databases for creep. For example, the development of new alloys and heat treatments effectively require a new database, which can take years to build. Fatigue databases can be built relatively quickly, but geometric configurations and loading conditions present other challenges; specifically how the data is interpreted for actual engine operation.

The interaction between creep and fatigue in a land based gas turbine combines all these challenges and as a result, it is an area of consideration which is under constant development. Historically, these considerations have been addressed with some conservatism at the design stage. However, as operators expect more capability and value from their land based units, it has become imperative that OEMs improve their understanding of this behavior. As our industry moves forward with ever greater challenges, it is important that we continue to develop our capabilities in close partnership. This can be achieved through the collection and management of operational data and the continued development of new lifing approaches to provide operators with confidence in the reliability of their assets.

This paper presents a brief description of material ductility, the rate dependence and how it can be used to calculate damage. Typical load cycles for land based gas turbines are described, including a scenario where creep and fatigue interact through perturbation of the stress-strain cycle. The calculation of creep-fatigue damage is then presented for a typical gas turbine cycle. Finally, consideration is given to the implications for asset management and the challenges that need to be overcome prior to successful implementation of this approach.

NOMENCLATURE

ε_{pl}	Plastic Strain
ε_{cr}	Creep Strain due to Relaxation
ε_{c}	Creep Strain at Constant Stress
ε_{f}	Available Ductility

t	Time
λ	Damage

DUCTILITY EXHAUSTION

Traditionally, gas turbine component durability is determined through the calculation of damage mechanisms such as creep and fatigue. These mechanisms are typically considered independently, where the influence of creep or dwell time is not considered on fatigue and the influence of cyclic loading is not considered on creep. For components that are subjected to large stress ranges and dwells at high temperature the independent approach is challenged, in providing a reliable prediction for damage and therefore, durability. It is the interactions of these damage mechanisms that can result in significantly more damage than the independent approach would predict. Failure to account for this can lead to inaccurate predictions for component life and therefore, the potential for unplanned down time increases. Mixed damage models are available (Holdsworth, 2015, Levaillant et al., 1998, Webster and Ainsworth, 1994) to account for these interactions, one of which is ductility exhaustion, and the focus of this paper.

What is ductility? Ductility is the total available strain for a given material and material condition (i.e. heat treat). Ductility has long been used to assess material stability, for example, Griffith's (1921) approach to brittle fracture. Ductile materials are often used in highly demanding environments for damage tolerance. This is certainly the case for gas turbine engines and Superalloys which have been specifically designed for this purpose. Ductility is dependent on a number of variables, including temperature and strain rate. It has been shown that strain rate dependence relates to both creep and fatigue damage (Spindler, 2004). Higher strain rates are related to dislocation driven damage mechanisms, and lower strain rates are related to diffusion driven damage mechanisms. Fatigue damage is therefore dominated by high strain rates and dislocations, whereas, creep can occur over a range of strain rates, but is typically dominated by diffusion or lower strain rates.

Figure **1** presents a typical ductility curve relating available ductility to strain rate.

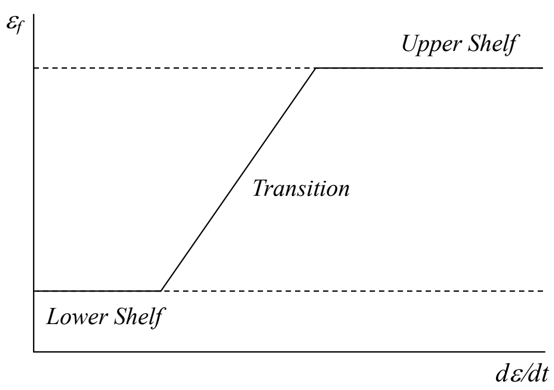


Figure 1: Idealized Ductility Curve.

Typically higher strain rates exhibit more ductility and lower strain rates exhibit lower ductility. This behavior can be seen when comparing material test data, for example, tensile tests will generate the greatest amount of ductility, however, long term creep tests, performed at low strain rates, generate less ductility at rupture. However, the ductility range is bound between lower and upper shelves, where ductility is insensitive to further changes in strain rate. At intermediate strain rates, both dislocation and diffusion mechanisms are active, resulting in a transition region that connects the lower and upper shelves. An advantage to this approach is that available ductility (or damage) can be determined at any strain rate. This simplifies the approach to creep and fatigue by normalizing damage relative to strain rate. Other variables such as temperature and multi-axial stress states can affect ductility, however; the basic principal is universal.

This method is used extensively in the UK Nuclear industry for stainless steels and is fundamental to the industries life assessment procedures (Ainsworth et al., 1995). In applying this methodology to gas turbines, it was discovered that Superalloys behave similarly. During development, several Superalloys were assessed for strain rate dependent ductility, which included both isotropic and anisotropic materials.

Figure **2** shows an example of a typical Superalloy used in land based gas turbines.

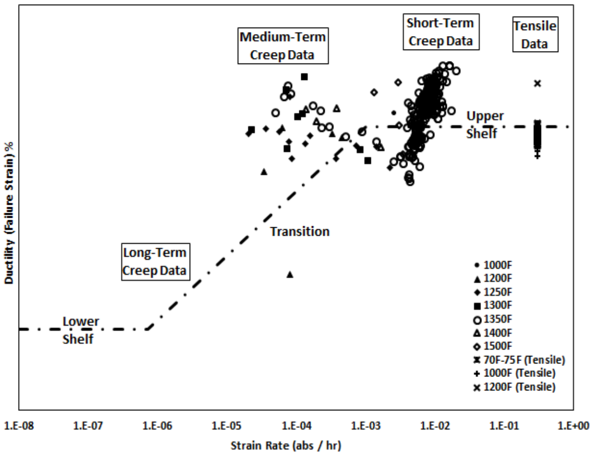


Figure 2: Initial Ductility Curve for a Typical Gas Turbine Superalloy.

As can be seen in

Figure **2** the Superalloy exhibits the characteristic upper shelf and transition region. However, populating the lower shelf is challenging due to the inherent strength of

Superalloys. This requires creep testing at very low strain rates, (typically $<1 \times 10^{-7}$ in/in/hour) which is equivalent to creep tests run to hundreds of thousands of hours. Understanding long terms creep data is a challenge which has faced the gas turbine industry for many years and is not exclusive to this methodology. As discussed previously, challenges associated with time for long term creep testing, leads to practical approaches based on extrapolation of creep data being the typical solution to this problem. There are many models available for predicting the creep response beyond the data sets available and these models can be used as part of the ductility exhaustion approach (e.g. MMG or Norton etc. Reed, 2008). The issue of lower shelf ductility can be addressed through the application of design knowledge and operational experience within realistic periods, such as service intervals. Despite these challenges, there are significant advantages to this method over traditional independent approaches.

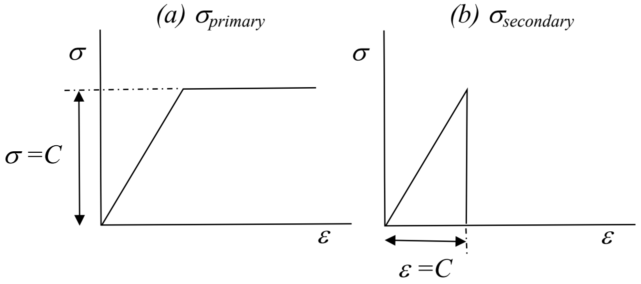
Damage is defined as the exhaustion of available ductility over the period considered. Calculation of damage can be performed through the ratio of incremental strain to available ductility at a given strain rate. This can be accumulated over the operational period to provide a damage fraction, see Equation 1.

$$\lambda = \int_0^t \frac{\dot{\varepsilon}}{\varepsilon_f\left(\dot{\varepsilon}, T\right)} dt \qquad (1)$$

Typical operational periods have multiple start and shut down cycles with dwell periods. This results in variable strain rates and ductility. For engine start up and shut down cycles, which are dominated by fatigue, the strain rates are relatively high and are managed by the upper shelf region. Conversely, dwell periods, which are dominated by creep, have lower strain rates and will be managed by the lower shelf and transition regions. By combing damage calculations for both these conditions, it is possible to define a single, interdependent damage fraction. The following sections discuss how creep and fatigue damage can interact within a gas turbine component subjected to high temperatures and mechanical loads. However, it is first important to consider how stresses in gas turbine components behave under different loading conditions.

STRESSES IN GAS TURBINE COMPONENTS

Hot section components experience two principal load conditions, arising from mechanical loads, such as speed, and thermal loads from high temperatures gradients. These load conditions result in primary and secondary stresses. Primary stresses are attributed to mechanical loads and are considered to be constant at steady state conditions.



Secondary stresses are derived from displacements, such as thermal gradients, and are not considered constant for steady state conditions.

Figure **3** illustrates the idealized engineering stress-strain response of a material subjected to constant primary and secondary stresses.

Figure 3: Engineering Stress-Strain Response of a Material Subjected to Constant (a) Primary and (b) Secondary Stresses.

In the case of primary stresses,

Figure **3**(a), the strain varies over time, (neglecting any redistribution and Poisson's effects), resulting in creep. In the case of secondary stresses,

Figure **3**(b), the strain remains constant, and therefore stress varies over time, resulting in relaxation. Typical components are subjected to both primary and secondary stresses and will exhibit strain accumulation through creep and stress relaxation. The relative contribution of primary and secondary stress is dependent on the component and location in the engine. Typically, hot section static components are dominated by secondary stresses, whereas rotating hot section components are dominated by primary stresses. However, it is important to note that the stress state of any component, whether static or rotating will be dependent on the design of that component and the subsequent loading cycles.

Figure **4** illustrates how static and rotating components may respond over time to a constant load resulting in both primary and secondary stresses.

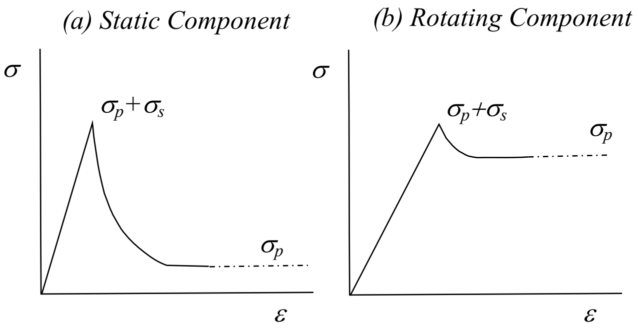


Figure 4: Typical Stress-Strain Response of (a) Static and (b) Rotating Components Subjected to Constant Load.

For static components, dominated by secondary stresses, the relaxation is significant, reducing peak stress substantially down to the primary stress component over time, (i.e. pressure loads etc.). For rotating components, speed and therefore primary stress is dominant, resulting in less relaxation and more creep over the dwell period. The interaction between creep (primary stress) and relaxation (secondary stress) can have a significant effect on the cyclic response of components in the hot gas path.

It is important to understand the contribution of primary and secondary stresses as this has a significant influence on the cyclic response of the component. Typical operation of land based gas turbines results in multiple starts and shut downs, (major engine cycles) which lead to fatigue damage. Traditionally, fatigue damage is calculated independently from other damage mechanisms and is based on the cyclic stress or stain ranges along with a material endurance curve and possibly mean stress effects. However, this approach is limited, in that it does not account for stress relaxation over time, as fatigue is typically calculated in the frequency domain rather than the time domain. However, there are models available which account for this behavior and ductility exhaustion is just one example.

In addition to relaxation, there is also the consideration of plasticity which redistributes stresses with the advent of plastic strains. This is a function of both geometry and load and should be considered when taking relaxation into account. Elastic-plastic stresses at the start of the dwell period will influence the rate of relaxation. The damage induced from the plastic component of the stress-strain response can also be assessed along with the relaxation component as part of shake down. As both relaxation and redistribution act to reduce the peak stresses in the cycle, both should be considered in the component life assessment for the overhaul period.

CREEP & FATIGUE INTERACTION

For engine cycles with high temperature dwells within the service interval, there are many types of interactions between the cyclic and creep damage mechanisms. The most direct interaction is cyclic perturbation. This occurs when the fatigue cycle is perturbed as a result of relaxation due to creep. However, this phenomenon does not occur for all cycles or all components and is a function of the relative magnitudes of the primary and secondary stresses and the combination of load cycles.

For components that are typically driven by primary stresses, thermal gradients can introduce significant secondary stress. It is the secondary stresses which tend to relax quite early in the component life. Figure 5 presents the typical stress-strain response of a critical location within a primary stress dominated component.

Unloading of the component can result in compressive stresses at critical locations which return to the primary levels upon reloading and creep strain accumulation continues at predictable levels between unload and reload cycles. This is how gas turbine components have been lifed historically and does not require a combined creep and fatigue interaction model unless the subsequent load cycles change. In this example creep can be calculated independently from fatigue and vice versa.

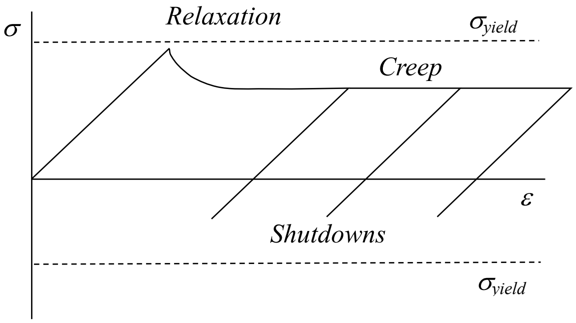


Figure 5: Idealized Stress-Strain Response of a Primary Stress Dominated Component.

For components that are typically driven by secondary stresses due to thermal gradients, the initial stress state also tends to relax quite early in the component life. As the relative magnitude of stress is biased towards the secondary stress, the resultant primary stress tends to be relatively low and as such, further creep strain accumulation at this low primary stress level results in significantly less damage.

However, complications can occur during unloading when the full elastic stress range is removed from the stress state at the end of the dwell. This has the potential to push the component into reverse plasticity, although this does not generally occur as the elastic stress range is insufficient to cause plasticity at both ends of the cycle. The potential for reverse plasticity only occurs due to relaxation. Instead unloading results in “pinning” of the cycle at the compression yield stress. Upon reloading, the full stress range (primary and secondary) is reapplied leading to a perturbation of the peak stress at the start of the next dwell period. This leads to further relaxation and additional creep damage. In extreme cases, this can lead to cyclic ratcheting of creep strain at every load - unload cycle, as shown in Figure 6.

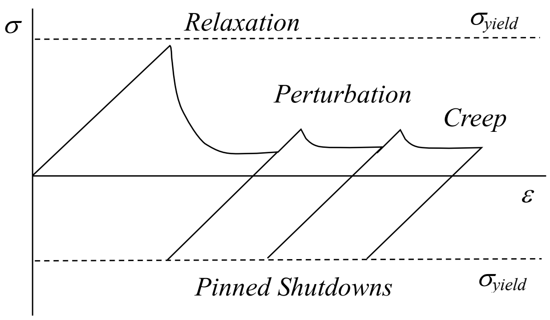


Figure 6: Idealized Stress-Strain Response of a Secondary Stress Dominated Component.

In both cases above, a simple repetitive cycle was assumed. However, in actual operation, there are many mixed cycles, where either speed and or thermal loading can vary. In these cases, the stress ranges vary, in both magnitude and composition, (primary and secondary stresses) resulting in the potential for perturbation of the peak stresses from one cycle to the next due to the path dependency of the damage accumulation. Figure 7 illustrates this behavior.

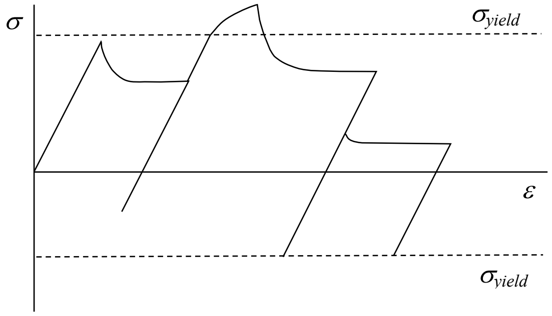
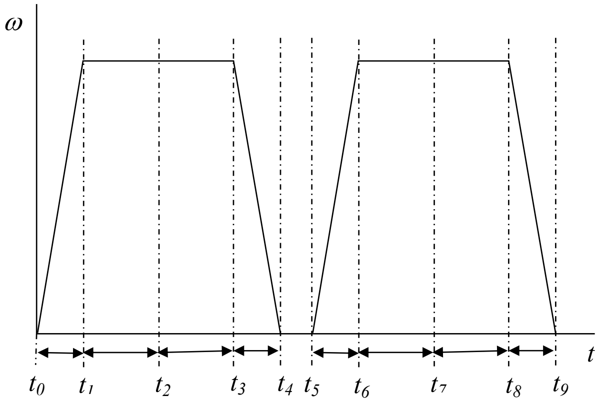


Figure 7: Idealized Stress-Strain Response of Component Subjected to Mixed Cycles Resulting in Perturbation.

It is important to note that damage accumulation is path and history dependent. The implication of this is that any event which is not accounted for as part of the load set could have a significant impact on the resulting damage prediction.

Therefore, a lifing methodology such as ductility exhaustion, as a nonlinear and path dependent model, is an ideal approach to managing creep and fatigue interactions of realistic cycles for land based gas turbines.



APPLICATION TO GAS TURBINES

Previous sections have discussed a rate dependent durability model for creep and fatigue and a method for decomposing load cycles into both thermal and mechanical components of stress. Combing these two methods provides a simple approach to predicting damage for realistic load cycles. Figure 8 shows an idealized load cycle for a land based gas turbine where assumed temperatures and stresses will be used to elucidate the concept.

Figure 8: Idealized Load Cycle for a Land Based Gas Turbine.

The load case above contains two identical starts with a dwell period of several days at full load conditions. The first step to assessing a components durability is to calculate the resultant stress and metal temperature during the cycles. This can be performed in a variety of ways, including tools such as transient finite element analysis. Component stresses and temperatures can be used to construct a stress-strain response at locations of interest as follows; Figure 9 illustrates a stress-strain response where the location of interest experiences a cyclic perturbation.

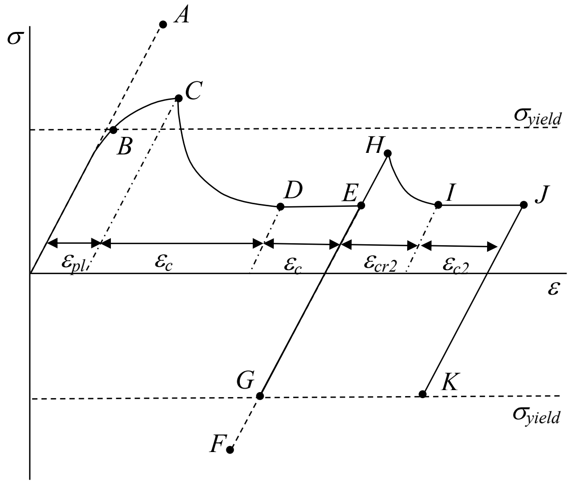


Figure 9: Stress-strain Response for the Idealized Load Cycle Resulting in a Perturbation.

The initial start conditions (t_0 - t_1) gives rise to an equivalent elastic stress range incorporating both primary and secondary stresses (*A*). This exceeds the yield condition (*B*) at the example metal temperature. Upon yielding, the location work hardens (*C*) and results in an equivalent plastic strain (ε_{pl}). Followed by a dwell period (t_1 - t_2) allowing relaxation from creep to the primary stress (*D*) resulting in equivalent creep strain (ε_{cr}). Further dwell ($t_2 - t_3$) results in additional creep strain (ε_c) at the constant primary stress condition, until the dwell period ends (*E*). At the end of the dwell period the engine is shutdown ($t_3 - t_4$), where the entire equivalent elastic stress range is unloaded to a point below the compressive yield (*F*). However, as discussed, the equivalent elastic stress range is insufficient to cause yielding at both ends of the cycle, so reverse plasticity does not occur and the equivalent elastic stress range is pinned (*G*).

Upon reloading ($t_5 - t_6$) the full equivalent stress range is again applied, resulting in a perturbation (*H*) with a start of dwell stress greater than the primary stress. This results in further relaxation ($t_6 - t_7$) and additional creep damage (ε_{cr2}). Once relaxed (*I*) creep strain (ε_{c2}) continues to accumulate for the remainder of the dwell period ($t_7 - t_8$) until shutdown (*J*). Again reverse yielding does not occur and the equivalent stress range is pinned at the compressive yield (*K*).

Further application of this load cycle would repeat this behavior with a perturbation of the stress state at the start of dwell, followed by relaxation resulting in additional damage.

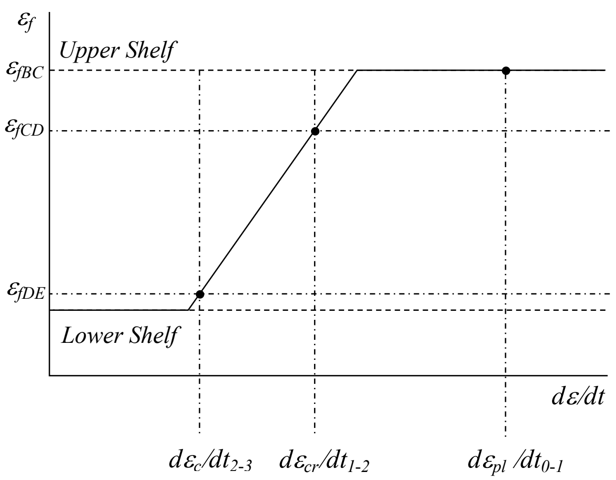


Figure 10: Identification of Available Ductility at Relevant Strain Rates.

Once the stress-strain response is defined, damage can be calculated using the materials ductility curve, the stress-strain response and the load cycle periods.

To calculate the damage for the initial part of the load cycle, identify the plastic strain from the start up (ε_{pl}) and the period over which the strain occurred (t_0 - t_1) and determine the strain rate ($d\varepsilon_{pl}/dt_{0-1}$). Referring to Figure 10 identify the available ductility (ε_{fBC}) for the calculated strain rate. Damage is determined as the ratio of available ductility to the incremental strain (λ_{0-1}). Moving to the relaxation component of the stress-strain response, the process can be repeated. Identifying the creep strain (ε_{cr}) and the period over which the strain occurred ($t_1 - t_2$) the strain rate ($d\varepsilon_{cr}/dt_{1-2}$) can be determined. Again, referring to Figure 10 identify the available ductility (ε_{fCD}) for the calculated strain rate and determine the damage fraction (λ_{1-2}). Repeating the process for the remaining inelastic component of the stress-strain response ($t_2 - t_3$) will generate a damage fraction for steady state creep (λ_{2-3}). As no inelastic component occurred during shutdown the total damage fraction for the first cycle, is the sum of the plastic, relaxation and creep damage fractions.

Moving to the second cycle and repeating this process will generate damage fractions for the relaxation and steady state creep components of that cycle. The total damage fraction is a summation of both cycles. If additional cycles are added to this sequence, then the process is repeated to determine the damage fractions for each new cycle.

It is worth noting that in the example used, perturbation occurs due to the magnitude of the equivalent stress range. Further perturbations may occur between engines cycles in a similar way, if the temperatures and stresses change sufficiently. Figure 11 illustrates how perturbation can occur between two different engine cycles with varying magnitudes and compositions of stress.

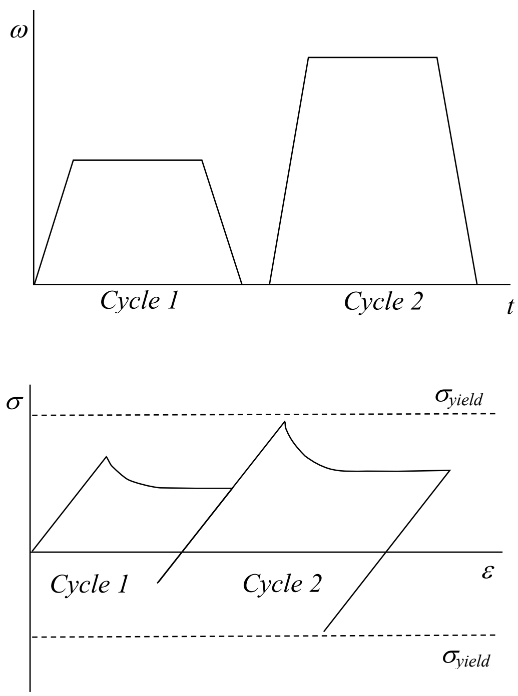


Figure 11: Perturbation due to Different Engine Cycles.

This approach fits well with land based gas turbine operations due to the nature of the load cycles. Typically, land based units exhibit significant dwells periods at high temperatures between major engine cycles within a given service interval. As discussed, this gives rise to creep and fatigue damage which can interact.

The ductility exhaustion approach is flexible, allowing for a range of different operations. Providing a consistent model for either high cycle operation or operations containing long dwell periods. Furthermore, the model is adaptable, and can be easily scaled to assess modifications to operational profiles. Traditional approaches independently assess these operations based on the dominant damage mechanism. Load cases with long dwells would use a creep damage model, whereas, load cases with high cycles would use a fatigue damage model and as discussed, potentially miss interactions.

Another benefit of this approach is consistency across component types, providing a standardized method for all high integrity components regardless of application. This offers additional validation opportunities as the approach is material based and can therefore be compared across multiple components of the same material. This increases confidence in the model over time.

This approach provides a simple durability calculation for variable load histories because all that is required is the calculation of strain rate for each load condition. Strain rate calculations can be performed in a variety of ways, including finite element analysis. Once calculated, it is possible to find the available ductility and the subsequent damage fraction from material data curves.

IMPLICATIONS FOR ASSET MANAGEMENT

The previous sections established the benefits of using ductility exhaustion for land based gas turbines. The flexibility of the approach provides an ideal platform for assessing load histories through the accumulation of incremental damage fractions. As damage fractions are representative of an actual load case, it reduces the need for models based on damage per hour, which tend to be built on operational assumptions. The intent of life prediction models is to provide a remaining useful life (RUL) value. Therefore, models with improved accuracy from the assessment of realistic load cases provide much greater confidence in the RUL predictions. However, in order to provide an accurate and safe calculation, an understanding of the mix of cycles making up the load history is required. Failure to understand the operational profile of the engine may lead to inaccurate life predictions. Therefore, it is imperative that engine operational data is reliable and available.

Other challenges to this approach include computationally efficient approaches to predicting stresses and temperatures. Although data can be collected from engine operation in a variety of ways, processing the data to generate stresses and strains which are required to predict damage is currently computationally expensive and time consuming. Additionally, methods for managing uncertainty and variability need to be developed in order to provide confidence in the calculations. Traditional approaches to dealing with uncertainty still apply, such as material data variability and engineering calculations. However, approaches need to be developed which deal with operational uncertainties, for instance, engine data quality or the availability of instrumentation. It is also important to note that the ductility exhaustion approached presented in this paper, does not currently include environmental considerations. It is known that engines can operate in harsh environments, which can contribute and influence damage mechanisms. All these challenges are being considered as part of ongoing work.

SUMMARY

An approach has been presented to predict remaining useful lives (RULs) of land based gas turbines components based on ductility exhaustion.

Superalloys have been shown to exhibit rate dependent ductility. This behavior can be used to calculate damage for a range of operational load cases. Due to the rate dependent nature of the material data, a single method can be used for assessing both fatigue and creep damage including damage resulting from interactions between the two mechanisms.

Due to the path and history dependent nature of the approach, it is well suited to processing actual engine operation data. However, there are still challenges associated with obtaining and processing large data sets. Data quality and availability are critical to implementing this approach successfully. Nevertheless, this approach is effective for design cycles, producing a similar result to equivalent operating hours, where assumed operational profiles, based on general use cases, combined with a probabilistic approach can be used to predict damage. It is important to note that this approach is flexible and provides functionality for a range of inputs.

Further work is required to i) improve computational efficiency to provide a path to modeling large data sets and ii) expand the damage fraction approach to include other damage mechanisms, to account for environmental considerations.

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