GE Power

Design and Operation of Large Fossil-Fueled Steam Turbines in Cyclic Duty

July 2016

Cuong Dinh, Brian Marriner,
Randy Tadros, Simon Yoongeu Kim
and Thomas Farineau

Table of Contents

Abstract

Most large modern, fossil-fueled turbine-generator trains now operating in the United States entered service as the most efficient and reliable machines in their system, and were designed to operate in a base-load mode during initial service. Today's demand for operational flexibility has driven the existing units in the fleet to cycle more frequently than to operate in a base-load mode. Many of the past units entered some form of cyclic duty as larger and more efficient units were brought on line. Recent changes in the cost economies of fossil fuels have caused traditional operating practices of these large machines to change substantially. System power demands as well as high fuel costs require that many units now entering service be capable of being operated in a cycling mode from the day they enter service. Unfortunately, units shipped approximately before 1975 to 1980 are not designed for cyclic operation, or not designed with rotor features to accommodate moderate cyclic duty. Cyclic duty like two-shifted operation was incorporated into design practice in around early 1980's.

Experience in the 1950s and 1960s with thermal cracking of the heavy metal parts of the turbine, together with analyses and studies, have resulted in a better understanding of how to reduce the damaging effects of thermal stresses caused during cyclic duty. This work has led to improved designs of component parts that are capable of providing the flexibility required by cyclic duty.

One of the most challenging areas in this regard has been the design of large, opposed-flow HP-IP units suitable for the various types of cyclic duty encountered today. With a steam generator having an adequate steam temperature control capability and variable pressure control, large combined HP-IP turbine element designs can meet utility industry cycling requirements. However, GE recommends that a funded study for cyclic duty and frequent inspections of the components are performed in order to get a specific understanding of the fit for cyclic duty.

Introduction

Background – Trend of Current Fossil Power Plants and Operation

Recently, many large fossil-fired steam turbine generating plants have been operating in cyclic mode. These large fossil-fired units entering service were more efficient and reliable than other older units, and have historically operated in a base-load mode during the initial life of the units. Daily or seasonal variation in peak load demands have necessitated cycling of these older, smaller, and less efficient units, and many of these units are operated in this manner. Eventually, the larger "base-load" units have entered some form of cyclic duty. During recent years, the interest in cycling operation has increased due to concern over cost and availability of fossil fuels, as well as power demands driving more efficient unit availability and flexibility.

In the late 1950s and early 1960s, analyses of thermal cracking problems occurring in turbine parts provided a better understanding of the mechanism of damage due to thermal stresses. Much work was published in the literature, which further increased the understanding of cyclic thermal stress—i.e., the concepts of cumulative cyclic damage, and bore stress limits. This understanding has resulted in a number of major design changes which have significantly improved the ability of the turbines to resist thermally induced surface cracking. In spite of rapid growth in unit rating during this time, the design changes have resulted in overall reduced level of cyclic damage for a given load transient. Figure 1 summarizes this effect, and Figure 2 shows reference load cycle.

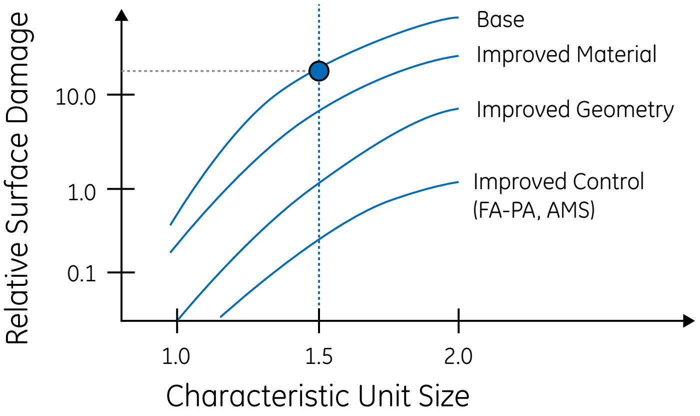

Figure 1. History of design changes to improve rotor surface cracking resistance.

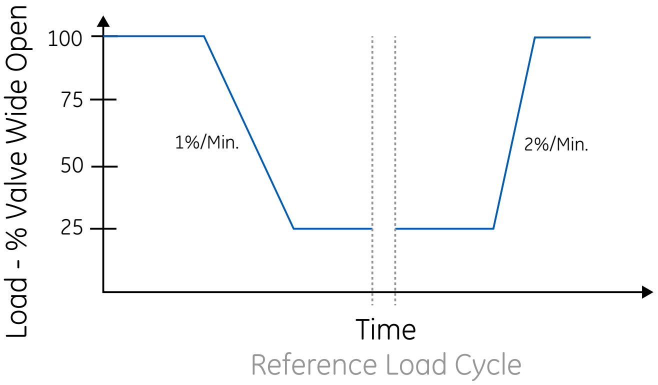

Figure 2. Reference load cycle.

The modern material of choice for high temperature application is Cr-Mo-V alloy, as this material is more fatigue-resistant compared to previous material used. On a relative scale, this improved the resistance to the surface thermal fatigue damage by an order of magnitude. Another change involved the redesign of the critical wheel fillet region of the rotor geometry. This reduced stress concentration (Kt) on the wheel fillet region and improved fatigue resistance by another order of magnitude. With the introduction of full-arc admission first stage control, the amount of cyclic damage could be further reduced.

System Cyclic Requirements / Need for Cycling of Large Fossil Units

In today's operating trend, it is important for the customer to be cognizant of the operating profile and costs involved; there will be situations where the unit has to respond quicker to changes in system load, or where the unit will either be shut down or operate at a minimum load. The need to continuously adjust the output of a particular unit results from the ever-changing demand for electric power throughout the day. There are operational strategies that can be employed to satisfy the changing system demand.

Based on this system demand, today's fossil-fueled turbines are operated in various modes of operation including two-shift cycling, load cycling and high load operation. Two-shift cycling refers to when the unit is shut down overnight or during weekends. Load cycling refers to when the unit is unloaded overnight down to a minimum stable load. In addition to major overnight load reductions or shutdowns, fossil-fired units may be subjected to several smaller load changes, between 10 to 25 percent of the rating, during the day. Attention should be paid to the potentially high number of these load changes that may occur. It is likely that both modes of cycling duty will be experienced during the lifetime of large fossil-fired units.

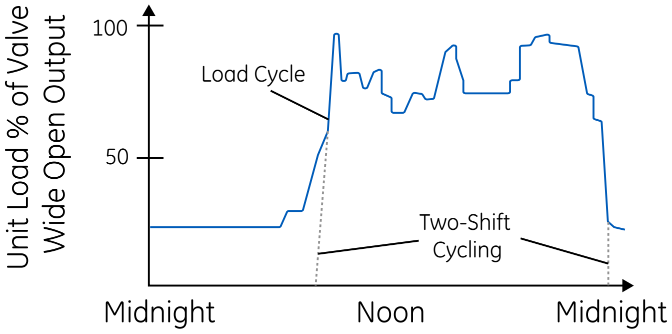

Figure 3. Two-shift cycling/load cycling.

Experiences of Cyclic Operation and Modifications

In the past, GE has performed studies to determine modifications and additions that would be required to protect steam turbines during cyclic operation. Some of the more significant modifications considered were:

- Modifications to rotor geometry to reduce concentration of stresses during transient events.
- Implementation of full-arc admission of steam to the turbine to reduce cyclic thermal stresses in high-pressure inlet and first-stage regions.
- Installation of additional boiler and turbine instrumentation and recording provisions. Thermocouples were installed to obtain temperature measurements at critical locations during thermal transients. In addition to various turbine locations, a special furnace temperature probe was installed to monitor flue gas temperature in the superheater section during cold starts.
- Installation of an automatically controlled valve in the cooling water line to the generator heat exchanges for hydrogen cooling.

These modifications were based on studies performed for specific units, and could vary based on code type and modifications performed. However, it is likely that there are many units being operated in combined cycle without the studies being performed. Because no modification is performed on these units, in addition to lack of understanding in steam turbine's fit for cyclic duty, the risk of steam turbine damage becomes greater.

Future Operation

Units shipped approximately before 1975 to 1980 are not designed for cyclic operation, or not designed with rotor features to accommodate moderate cyclic duty. Cyclic duty like two-shifted operation was incorporated into design practice in around early 1980s. As mentioned, cyclic operations that include very frequent startup/shutdown can be very damaging to steam turbine components. Thus, today's turbine design must address the challenge of providing satisfactory cycling flexibility over the entire life of the machine, yet at the same time provide a reliable machine that will achieve and maintain high thermal efficiency. It should be noted that today's large fossil-fueled steam turbines, including those with opposed flow HP-IP rotors, have evolved to a point where they incorporate many of the positive features originally developed for the two-shift designs. In addition, current designs have the ability to select full-arc or partial-arc admission at any load. This progress has led to the development of modern, efficient, opposed flow HP-IP units which are well suited for cyclic duty.

Nonetheless, even though more of the modern designs have incorporated the aforementioned features that are favorable for cyclic duty, it must be understood that cyclic operation can still be damaging to existing equipment. It is important for the customer to communicate with the OEM if extensive cycling is planned for expected future operation. It is also a good practice to inform the OEM on how many cycles and operating hours have accumulated since commissioning. The objective is to satisfy system demands in an economical manner without unduly shortening the useful life of major turbine components.

Many of the recent units are designed using modern finite element analysis (FEA) tools and methods. As FEA tools and methods were not available during unit design for the vintage units of 70s through 80s, these tools/methods can also be used to determine remaining life on components from units during that have been in operation for the past 30 to 40 years. This can be part of the feasibility study for cyclic duty and remaining life assessment study.

Impact Of Cycling On Turbine – Cumulative Cyclic Damage

Governing Components for Cyclic Duty Operation

The ability to start and load the turbine-generator in accordance with system power requirements is one of the most important factors in the selection of the type of cyclic duty once a unit has been designated for cycling. If the minimum plant load is reduced for overnight low-load operation, the turbine is generally not the limiting factor in either load manoeuvring rates or attainable minimum load. However, from an operational point of view, there are several types of turbine-related limitations during rapid load changes, shutdowns, and startups including thermal stress, differential expansion, and rotor vibration.

Experience with modern designs have shown that startups as well as load changes are not limited by differential expansion, and rotor vibration is not a limiting factor during cyclic operation with a well-balanced unit. The governing components for cyclic operations include: high pressure (HP) and reheat (IP) rotors and shells; valves including main stop valve, control valve, reheat and intercept valves; and LP rotors. It is generally recognized that the most critical turbine limitation during cyclic duty is the development of transient thermal stresses in the large, high temperature components, particularly the rotor during heating and cooling.

The control valve chest tends to cool more rapidly than the main turbine, and hence has to be heated more during startup. This effect is more pronounced for longer shutdowns. Modern units, which are equipped with provisions for full-arc, partial-arc startups under control valve control, are also equipped with provisions for control valve chest prewarming on turning gear. This allows warming the chest to approximately the same level as the turbine prior to rolling the unit. Subsequent loading will not be limited by control valve chest considerations.

The hot inlet parts of HP-IP turbine shells experience approximately the same thermal transients as the rotor. However, design features such as separate control valve chest, separate nozzle boxes large fillet radii, reduced shell flange thickness, and provisions for full-arc rolling and initial loading result in shell designs which do not limit startup rates. The most limiting component during cycling component then is the rotor. Thermal stresses have the potential to cause unnecessarily high rotor bore stresses or local surface yielding, which if severe enough, can result in premature initiation of surface cracks. It is the fundamental purpose of all thermal stress-related limits to minimize the probability of these kinds of damage occurring during the economic life of the involved parts.

Analysis of Thermal Stress Limitations of the Rotor

The critical regions for potential surface cracking are the wheel fillets in the higher temperature stages of the high pressure and reheat sections of the turbine. The damage mechanism which initiates surface cracks in the region is primarily low cycle, and is dependent on the rotor geometry. Starting and Loading Instructions for large turbines have incorporated a Cyclic Life Expenditure (CLE) concept for many years, which is used to describe the amount of cumulative surface fatigue damage that is present and which can subsequently lead to surface crack initiation. Figure 4 shows cycle life expenditure based on the thermal surface stress/strain range.

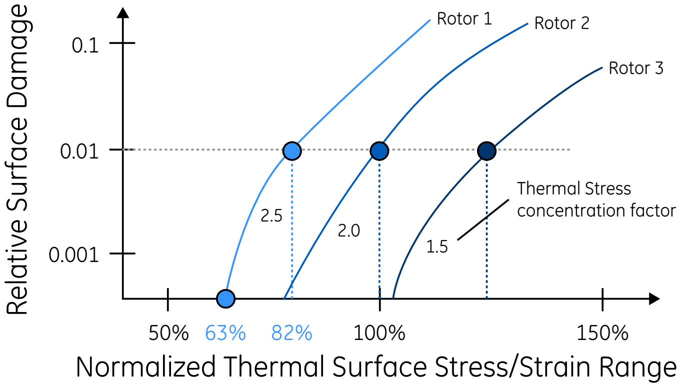

Figure 4. Effect of thermal stress range and concentration factor on cycle life expenditure.

Once a crack initiated on the rotor surface, high tensile thermal stresses developed during surface temperature reductions, along with superimposed high cycle alternating stresses caused by gravity bending, can lead to accelerated crack growth in rotors. This condition is unacceptable and all surface thermal stress limits must be conservative to avoid premature initiation of surface cracks.

The second consideration is related to the rotor bore region. Figure 5 illustrates a typical bore stress limit that is used to define operational guidelines.

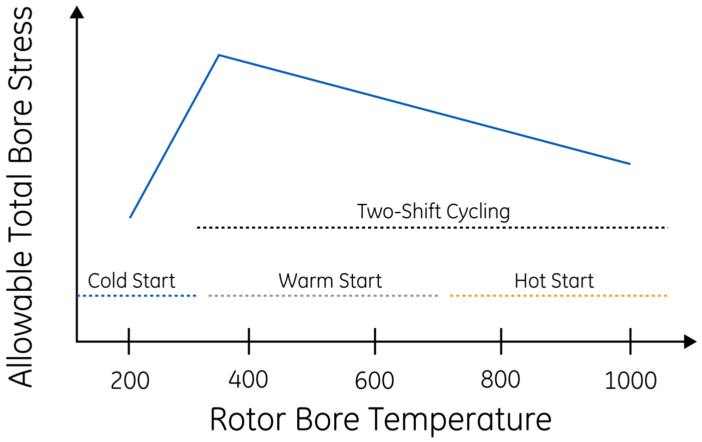

Figure 5. Allowable total bore stress for operational guidance.

The slope of the curve in the temperature region relevant to two-shift cycling is due to the temperature dependence of crack growth rate. This region of the bore stress limit is intended to prevent the development of critical bore cracks during normal operation. Occasional operation in excess of the limit in the higher temperature region may not necessarily lead to a failure, but rather tend to accelerate the initiation and/or growth of bore cracks. In the low temperature region, the main concern is for brittle failure, which is encountered during infrequent cold starts.

Bore stress is tensile in nature during temperature increases, and it adds to tensile centrifugal stress and presents a real limit during startups and other situations where temperature increases occur. It should be noted that there is scatter in material properties, as well as variation in turbine operation modes, which will require engineering judgment to adequately define the bore limit curve for a particular rotor.

Thermal Stresses in Turbine Rotors during Operation

Rotor stresses result from both centrifugal and thermal transient effects. Thermal stress on the rotor outer surface results from changes in the surface temperature associated with startup and load changes. For a typical cold start, the rotor surface and bore temperatures are near room temperature. When the unit is rolled and loaded, the rotor surface temperature increases rapidly compared to the bore temperature, producing an appreciable temperature difference between the average temperature of the rotor and the bore. This difference in temperature produces thermal stresses. The rotor surface stress initially is in compression because of hotter steam on the rotor surface, and cold start transient can cause the rotor surface material to yield in compression. This results in residual tensile stress when full-load, steady state conditions are reached. Figure 6 shows typical cold start stresses.

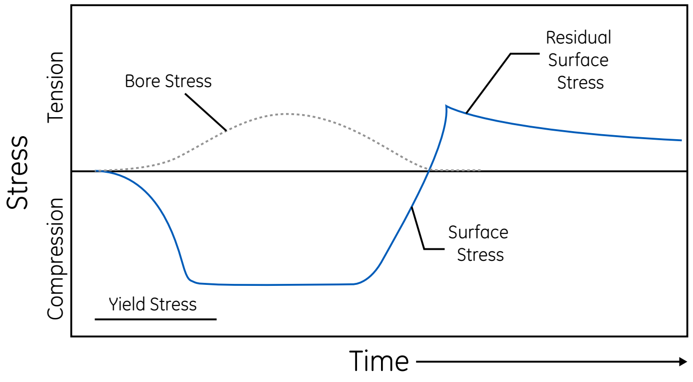

Figure 6. Typical cold start stresses.

For a hot start, the rotor surface and bore temperatures are initially higher than the first-stage steam temperature. This is typical for a fired boiler, as it generally cannot produce steam at a temperature high enough to match the initial turbine metal temperature. Initially, the rotor surface temperature drops rapidly as the first-stage steam temperature increases, and the rotor surface temperature reverses and increases. The rotor bore temperature lags behind the change in rotor surface temperature. During this cycle, the reversal of temperature difference causes a reversal in thermal stresses.

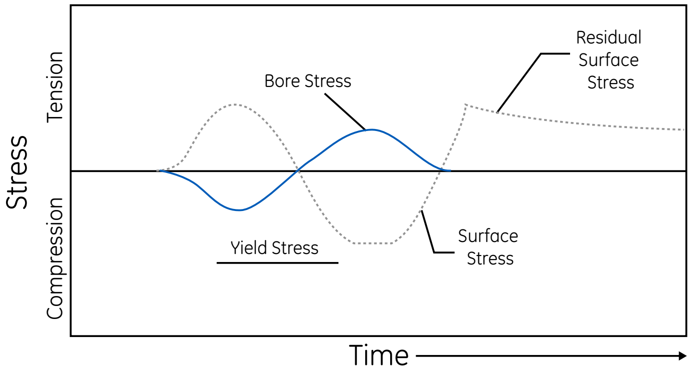

Figure 7. Typical hot start stresses.

In high temperature turbine rotors, the magnitude of the surface centrifugal stresses is low compared to thermal stress. However, there is significant contribution of centrifugal stress to the total bore stress, and the total bore stress in the high temperature region must be limited to prevent low cycle fatigue damage. In low temperature rotors, centrifugal stresses can be quite high beneath the wheels, whereas thermal stress can be very small due to low temperature.

Rotor Life – Finite Element Analysis

Rotor Material Strength – Low Cycle Fatigue

Fatigue is a phenomenon where a material weakens due to repeatedly applied loads, and when a material is subject to cyclic loading, localized cracks initiate and grow by the action of repeated stress. Low cycle fatigue (LCF) is associated with localized plastic behavior in metals; thus, a strain-based parameter is used for fatigue life prediction in metals. It should be noted that LCF consists of at least two parts
1 – repetitive centrifugal loading from start-ups and shut-downs; and
2 – thermal transients.

For the same temperature, the low cycle fatigue life is a function of the applied strain range and the mean stress. LCF cycle is referred to as any cycle that results in LCF life consumption such as a major startup/

shutdown. For a given material, a statistical minimum material property is used to determine the number of cycles to crack initiation as a function of % strain range (or equivalent strain range), as shown in Figure 8.

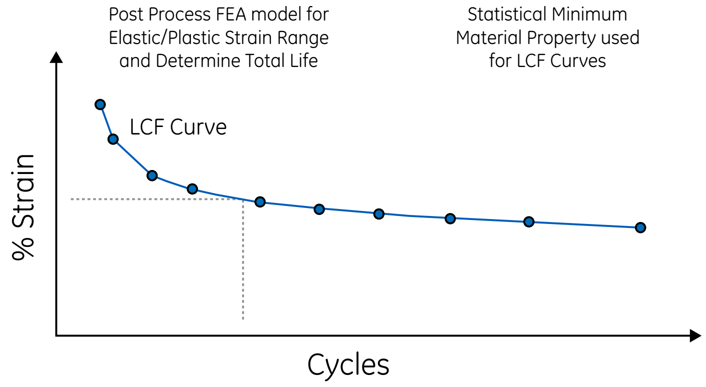

Figure 8. % Total strain range vs. cycles.

The number of cycles to cracking at high temperature is significantly reduced if a hold time (operating the unit at certain load/temperature) at the maximum strain is introduced. The LCF curve for the rotor material shows the total strain per thermal cycle vs. the number of identical cycles that would initiate thermal crack. Rotor fatigue life expended by past or future operation can be assessed by relating total strain to the thermal stress and thermal stress to temperature changes. It is possible to assess the life expended and to estimate remaining life based on rotor surface temperature changes.

Example of Finite Element Analysis

As mentioned, the rotors are regarded as the main limiting components. The three main areas of concern are surface stress, bore stress and bore temperature. To apply surface and bore stress limits, the operating centrifugal and thermal stresses at the critical regions of the rotor have to be determined. Stress analyses are performed using finite element analysis (FEA) methods to determine operating stresses. This typically includes creating both 2-D using Elastic-Plastic (EP) material properties for the rotor. The effect of complex rotor geometries and varying steam conditions on the rotor thermal stresses can be accounted for. Figure 9 shows a typical example of the finite element model used to determine the bore stress. Once the model is created, FEA is run for multiple load steps to determine operating stresses. Post processing is performed for elastic/plastic strain range and to determine total component life.

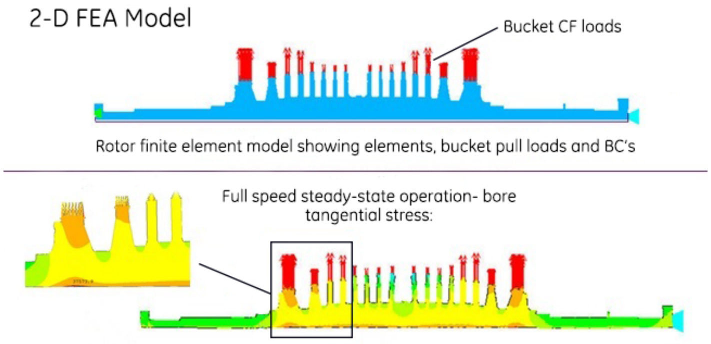

Figure 9. Example of rotor FEA model.

For the purpose of demonstrating the FEA process, an overnight shutdown-startup cycle is selected which represents the most frequently encountered situation during two-shift operation.

One of the most critical parameters for the analysis of thermal stresses during two-shift duty is the effective cooling of the turbine metal parts during the time between turbine trip and turbine restart. A reliable way to determine the effective cooling of various locations is by means of field measurements. From the assumed inlet steam temperature and pressure conditions in the HP and IP sections of the turbine, the steam temperature and pressure response at all regions of the rotor is established. Heat transfer coefficients at all regions of the rotor surface as a function of load are determined. Using the FEA method and this information, the temperature response of the rotor can be calculated. Axial temperature gradient exists at all times, and radial temperature gradient occurs during transient operation, with the maximum occurring near the end of shutdown and startup phase of the cycle. The results of FEA and isotherm lines are shown in Figure 10.

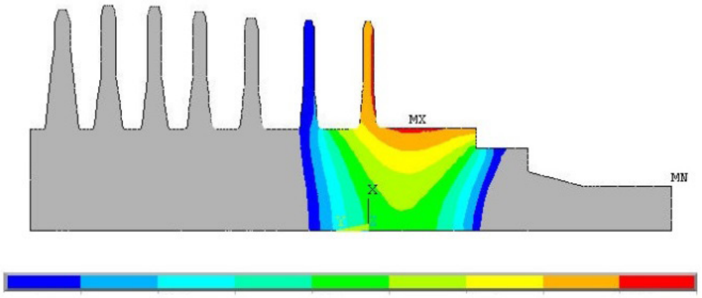

Figure 10. Example of isotherm lines.

Figure 11 shows the distribution of peak total bore stress along the rotor for the overnight starting as a percentage of allowable stress as defined for operational guidance. Allowable stress is dependent on temperature and varies during the cycle depending on the local bore temperature. Bore stresses are well within the allowable range and are a maximum near the end of the startup phase of the cycle.

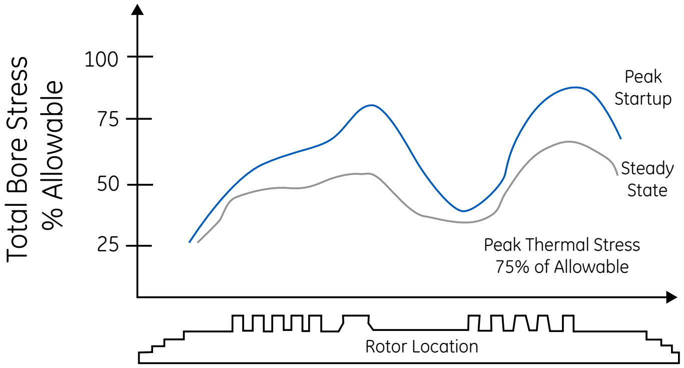

Figure 11. Total bore stress during overnight shutdown-startup cycle.

The maximum ratio of the bore stress as a percentage of the allowable is shown in Figure 12, as a function of time for the HP and the IP section. There is margin that exists during most of the cycle with the limit being approached only during the end of the startup cycle, indicating that the startup could be performed in less time without causing thermal overstressing.

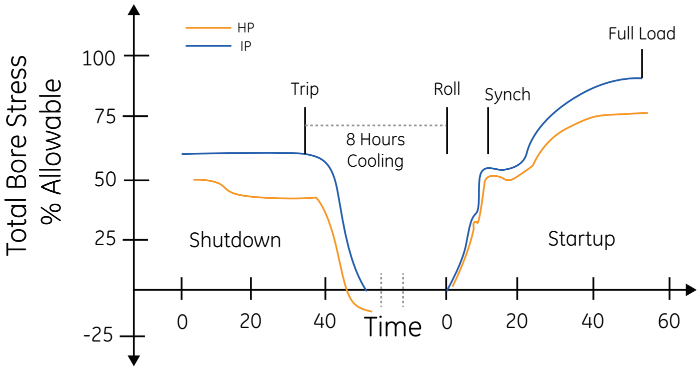

Figure 12. Peak HP-IP bore stress vs. Time during shutdown startup cycle (Finite Element Analysis).

The effect of wheel and wheel fillet geometry influences the level of low-cycle fatigue damage (Figure 5). From Figure 13, it can be seen that the total allowable stress range, which would produce a cyclic life expenditure of 0.01 percent per cycle is well above the analytically determined stress range, even if margin is added for the effect of possible sudden steam temperature spikes.

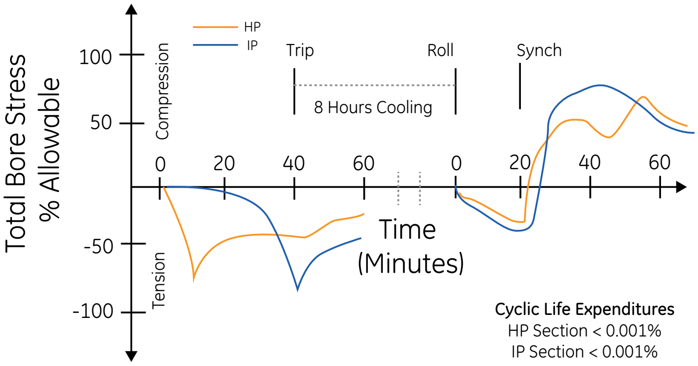

Figure 13. Thermal surface stress FEA.

Conclusion

While the aforementioned examples of finite element analysis show that there may be sufficient life remaining for the rotor's fit for cyclic duty, it should be noted that there are other factors that may impact the extended life of the existing steam turbine components, such as the mission mix/new operating profile, design, and the condition of the components. It is important that these factors are accounted for and that the steam turbine is inspected for structural integrity. Typically, a funded study on remaining life assessment and the requirement for non-destructive tests will reveal capability for cyclic duty.

References

J. Mora, K.M. Retzlaff and D.C. Gonyea "Design and Operation of Large Fossil-Fueled Steam Turbines Engaged in Cyclic Duty," ASME Joint Power Generation Conference, October 7-11, 1979, Charlotte, NC.

GER4933 07/2016