Steam Turbine Blade Reverse Engineering,
Upgrade and Structural Design

Eugene A. Chisely (Ph.D, PE)
Steam Turbine Thermal Services
Pooler, GA

Abstract

This paper presents a case study on the reverse engineering and upgrade of a steam turbine blade used in power generators. Blade reverse engineering is widely recognized a crucial step in the product design cycle. The blade surface reconstruction is an imperative process to develop mathematical models from existing physical objects for finite-element analysis, computational fluid dynamics and rapid prototyping in order to reduce product design lead time. Precise measurement of data point is very important in order to create a valid shape. Due to blade shape complexity, the resultant model geometry change can lead to large alteration in turbine performance. Therefore, control of blade shape is critical in the design process. The blade is a complex object and to generate an accurate simulation result makes turbine blade analysis challenging. Finite-element analysis is the accepted tool for turbine blade structural analysis. Both the model development upgrades and analysis will be presented.

Introduction

Turbine blade design involves blade solid model development, thermo-aerodynamics and structural mechanics disciplines. The process of the reverse engineering begins with determination of the function of the machine part, or capturing the design intent. Accuracy of reverse engineering data is limited by the applied measurement and computer–aided modeling techniques. A few of the major limitations are: in-service wear of the part, numerical, sensing, and approximation errors, as well as the applied manufacturing methods. In order to ensure and enhance blade integrity, optimized shape design of rotating and stationary blades is essential. This case study shall address the basic reverse engineering process and review two common examples of repairs and upgrades that are considered when aiming to improve mechanical reliability after blade damage is discovered.

The process for redesigning a steam turbine blade from a concept to an actual product is an iterative process. This includes; blade modeling with blade surface design to support Computer Aided Manufacturing programs (CAM), Finite Element Analysis (FEA) and, if necessary, Computational Fluid Dynamics (CFD). Throughout the design phase these iterative analyses are targeted to ensure reliability and performance. In some cases design modifications are required to achieve the specified output. As displayed in Figure 1, the necessary steps for turbine blade reverse engineering are similar to those used in a new-product development practice.
Turbine blades can present challenges to the manufacturers for even basic component reproduction. Blade design requires very consistent shapes, weights and geometries to avoid vibration stimuli and negatively changing performance characteristics. Modern blades are comprised of complex free-form surfaces, convoluted shapes, and very tight tolerances. In most cases traditional Coordinate Measurement Machines (CMM) can be used to accurately obtain geometric data of the sample. However, on complex airfoils, contact measuring devices have not proven to be capable of efficiently, nor effectively, gathering enough data points to create an accurate surface. Modern laser scanning technology has proven to be a suitable measurement method to capture the complex shape features of a turbine blade.

The process begins by gathering geometric information. A multitude of measurement tools and techniques are used to capture relevant data. For the airfoil, laser scanning is performed. The blade is scanned from multiple perspectives to allow surface continuity. After scanning, the point cloud data is aligned by mutual reference features. Once the assortment of scans are aligned and merged, a 3D surface is generated as displayed in Figure 2.
The point cloud data is edited by Geomagic Studio™. After automated and manual editing routines, a 3D surface is generated that represents the as-measured blade (see Figure 2, right side). The as-measured surface is used to produce the baseline model geometry. Curves used to construct the blade model are derived from cross-sectional planes as shown in Figure 3. A “perfect”, feature based, CAD model is necessary for programming the machining operations and finite-element analysis. The blade 3D solid model is displayed in Figure 4.
The entire CAD model is compared with the original scanned part to ensure the quality of the model. This step may vary based upon the incoming condition of the sample part. Parts with minimal wear, or known deviation from base design, can be quickly compared to start the iterative analysis. In the case of damaged or worn parts, further analysis may be required to generate a suitable base-line model.

In this case a new blade was measured. The inspection is performed with Geomagic Qualify™ engineering software with the geometric deviation displayed by color map in Figure 5. The comparison between the model and the original part indicates minimal geometric deviation. On the right side, the cross section planes are compared along the length of the airfoil for a detailed 2D evaluation. With a base-line model acceptable for analysis, the design can be evaluated and potentially optimized.
Tenon Design Inspection and Analysis

Each feature of the blade must be evaluated to determine its original design intent. Reverse engineering is not the reproduction of measured geometry, rather it is the approach for understanding the specific component’s or feature’s purpose. In many cases, redesign is required to overcome a specific failure mechanism.

The need for repair and replacement of steam turbine blades can stem from a variety of sources. Changes in vibration trends and section performance are the most common indicators of potential blade issues that can be discovered during operation. More commonly however, results from major overhaul inspections may identify immediate need for blade repair and replacement.

It is common for major overhaul inspections to include a variety of targeted Non-Destructive Tests (NDT) and dimensional inspections based on component criticality and equipment service experience. Blading inspections typically include surface inspections of the blade and its attachment area, volumetric inspections of surfaces that are not accessible, and dimensional inspection to detect movement or deformation. Collectively these inspections are used to gather information about the structural integrity of the parts and draw a conclusion to support development of a repair process specification. The repair specification can include either repair, in-kind replacement or redesign, depending on the situation.

For discussion purposes, an inspection of a blade’s tenon ultimately revealed indications at the tip of the blade at the tenon radius area. A section of the discovered crack is shown in Figure 6.

![Figure 6. Visual Examination Tenon Findings](image)

In this case, the crack is found to have initiated in the tenon to tip transition area. Analysis is needed to determine the mechanism of the crack initiation at the base of the tenon. Cracking in this area may be due various causes; original design, in-service conditions or even assembly.

In some cases, refurbishment is an acceptable alternative to component replacement. Refurbishment of tenons usually refers to fox-holing and weld repair approaches. Both solutions are widely accepted in the industry as appropriate
refurbishment techniques for reattaching, or re-securing, a new cover band to the existing blade.

Tenon weld repair offers the ability to reapply the original geometry. Repairs performed by welding alone may not prevent the tenon cracking while operating with the same boundary conditions. When a weld repair is chosen, one must ensure that the tenon geometry provides an adequate assembly fit and that the applied weld material and process are qualified and suitable for the operating condition.

Another repair solution is using a fox-holed tenon cover-band configuration (see Figure 7). This may only be considered if the applied stress level is acceptable. A 3D finite-element analysis of the fox-holed tenon design is displayed in Figure 8. Fox-holing tenons are a very economical repair approach, however, craftsmanship risk becomes an issue. Reuse of a riveted tenon requires careful assessment of remaining useful tenon height and profile. Blade distortion and manual establishment of the tenon profile may create cover fit issues that could lead to premature tenon failure. In some repair circumstances, where tenon cracking is observed, an undercut radius may be used as the tenon transition to avoid interference between cover-band chamfer and tenon fillet radius [2].

Figure 7. Tenon Fox-hole Configuration
Regardless of the maintenance decision, identifying the root cause of a failure is an important step that is commonly overlooked in the reverse engineering and design workflow. Understanding the damage mechanism is a critical aspect of a technical risk management program that is intended to support the economic decisions of equipment maintenance. Design of this rather simple tenon feature could have unintended consequences that lead to unexpected downtime and loss of generation if not managed properly during the design phase.

**Blade Attachment Inspection, Redesign and Analysis**

Another common example of a mechanical reliability enhancement or design optimization opportunity is the blade root attachment features. Redesign of a blade may be required due to a design weakness in itself or the mating component. Non-destructive testing (NDT) of blade steeples, either surface or volumetric, are traditional inspections performed during major overhauls. The remainder of this section will discuss a case whereby cracks had initiated at the transition radius of the steeple hooks in every hook. The size and orientation of the cracks are displayed in Figure 9. In order to modify the stress field at the cracked area of the steeple hooks, an optimized fir-tree steeple configuration is proposed.
The interface between a turbine blade and the disk represents one of the most critical loads within that assembly. Fir-tree blade configurations have been commonly implemented in turbines because they provide adequate areas of contact so that loads can be accommodated with a suitable design margin. Figure 10 displays a potential fir-tree blade and steeple configuration as a possible repair solution. The new blade base design is shown in Figure 11.
The design of the fir-tree geometry is carried out using a commercially available CAD package. The model is defined parametrically in order to incorporate live changes throughout the design optimization process. The basic hook engagement geometry is illustrated in Figure 12. In every step of the modeling process acceptability to design requirements are checked to make sure an adequate geometry can be generated. Otherwise, a geometry failure signaled the optimizer to cancel or modify the model and the analysis.

The blade root and the disk steeple geometry are defined in the same way as the basic tooth, with further parameters and rules applied. A sample of the geometric definition is displayed in Figure 13.
As the fir-tree steeple cross-sectional geometry is constant along the root centerline, it is possible to assume that the stress is 2D. However, the load along the centerline of the root is, strictly speaking, not 2D but rather 3D. Nonetheless, it is still reasonable to assume that each section behaves essentially as a 2D axial-symmetric problem with varied loading applied on the hooks [3].

In order to verify the feasibility of the fir-tree configuration, comprehensive 2D axial-symmetric (steeple) and 3D (blade) finite-element analyses are executed on the original and the redesigned fir-tree region of the blade disk assembly. The two primary outputs of this project are to create a geometric feature that can fit into the existing steeple domain, and to significantly decrease the notch stress concentration in order to increase the LCF (low cycle fatigue) life of the structure and reduce operational peak steady state stresses.

A two dimensional FE model is developed by using commercial ANSYS code as displayed Figure 14 and Figure 15. Axial-symmetric boundary conditions was applied. High mesh density is used throughout the interface region where a steep gradient in stress and stain are expected. The two-dimensional models are meshed with eight-node quadrilateral elements. The results of the finite-element analysis indicate that the peak stresses at the notch areas can be reduced significantly by implementing the proposed fir-tree root.
With the aim of ensuring accuracy of the finite element model solution, 3D blade model is developed as displayed in Figure 16. The turbine stage is comprised of grouped blade assemblies. To obtain an accurate solution it is crucial to simulate the real operating conditions in the model, especially when modeling a section of a large assembly. Cyclic boundary conditions are applied to the model to analyze the entire stage. Frictional contact elements are installed between the blade-steeple interface surfaces. The model is meshed with 10 node tetrahedron elements, where the contacting surfaces and the hook radius areas are refined to increase accuracy. All models are subjected to centrifugal loading by allowing the disk and attached blades to rotate with a specific angular velocity. In this example, the angular velocity (omega) was selected to be 3600 revolutions per minute.
The equivalent stress distribution of the base line and the fir-tree blade hooks are shown in Figure 17 and Figure 18. The results clearly indicate that by applying fir-tree root configuration, the overall stress level is reduced significantly. It is achievable to reduce the maximum notch stress by nearly 25% for the sample fir-tree design. The low cycle fatigue (LCF) life is thereby increased proportionately.
In multistage turbo-machinery, the interaction between the nozzle and the blades generates an excitation force on the blades, which comes from the wake of the upstream and downstream nozzles. The fundamental frequency of the excitation force due to the interaction between the nozzle and the blade is the rotor speed multiplied by the nozzle count. If the natural frequency of the blade coincides with the frequency of the excitation forces, the resultant stress on the blade may cause blade failure due to the high cycle fatigue (HCF). Modal analysis is a powerful tool to assist in the identification and elimination of the high cycle fatigue problem. In this study, finite-element analysis (FEA) was used to investigate turbine blade responses under running conditions. Finite element methods can be used to predict vibratory natural frequencies and mode shape. The rotor speed at which significant forced vibration may occur is predicted with frequency versus speed, or Campbell's diagram. This displays the natural frequencies of each blade vibration mode and the forcing frequencies as a function of the rotor speed as shown in Figure 19. The intersection of these curves indicates the integral order resonance points at which the possible vibratory stresses exist.

Any modifications to a blade’s form, fit and function must be assessed as if it is a new blade design. Proven design standards and analysis routines must be applied to ensure the mechanical integrity of the blade assembly based upon suitable operational boundary conditions. Without an adequate design program and suitable experience, initial design changes may correct specific issues, but oversights and assumptions during this phase may also lead to new problems and premature failure. Much like the tenon redesign, unintended consequences may lead to unexpected downtime and loss of generation if not managed properly in the design phase.
Summary

The repair and refurbishment decisions play a very important role in the economic management of steam turbine components. The underlying philosophy of the repair process is not to repair components that have reached the end of their design lifetime; it is to put back in service those components that have prematurely failed due to design, material, or manufacturing-related defects. Further, these repair and refurbishment specifications should be within the scope of the prevailing codes and regulations [4]. There is a growing trend for repair and reverse engineering facilities to move towards in-house production and the development of full-scale repair and refurbishment scope on steam turbine machinery. This activity requires not only engineering experimental, but also analytical capabilities from the reverse engineering techniques applied. This is achieved by using the latest repair technologies, precision measurement equipment as well as state of the art design and analysis tools. Rotating equipment failures cause millions of dollars of unrecoverable cost in lost energy production, plus additional millions of dollars paid in repair and replacement equipment cost. During a loss event, efforts are usually focused on restarting the unit to service as quickly as possible. It is important that a comparable effort is made to understand the failure root cause, and to use information that is gained by the failure occurrence to support future designs. Experience has conclusively shown where failed equipment is simply replaced with ‘identical’ components, the original problem is likely to be reinstalled and the failure scenario recreated [5]. Prudent blade design incorporates many engineering disciplines. Described within this paper are merely the general mechanical design considerations applied to blade repair and replacement projects. The engineering scope required to execute blade replacement or upgrade projects will vary depending on the nature of the damage mechanism, contractual guarantees, and technical risk. All three impact cost estimate generation and subsequently the economics of blade replacement projects.
References:

1. Liang- Chia Chen, Grier C.I. Lin , “Reverse engineering the design of blades- a case study in applying the MAMDP, RCIM 16 (2000), 161-167


