Steam Turbine Blade Design

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Abstract - This paper addresses the issue of steam turbine efficiency by discussing the overall design of steam turbine blades with a specific focus on blade aerodynamics, materials used in the production of steam turbine blades, and the factors that cause turbine blade failure and therefore the failure of the turbine itself. This paper enumerates and describes the currently available technologies that enhance the overall efficiency of the generator and prevent turbine failure due to blade erosion and blade cracking. In particular, this paper evaluates the effectiveness of certain titanium alloys and steels in resisting creep and fracture in turbine blades. The effectiveness of chemical and thermal coatings in protecting the blade substrate from corrosion when exposed to wet steam will also be addressed. The stresses developed in the blade as a result of steam pressure, steam temperature, and the centrifugal forces due to rotational movement are delineated; current designs calculated to counter the fatigue caused by these stresses are presented. The aerodynamic designs of both impulse and reaction turbine blades are compared and contrasted, and the effect that these designs have on turbine efficiency are discussed.

Based on the research presented herein, this paper presents a detailed summary of what modifications to existing steam turbine generator blades can be made to increase turbine efficiency. Finally, the overall sustainability of steam turbine generators is discussed and the impact that the design of the blades has on the sustainability of these generators is presented.

Key words- Blade, efficiency, corrosion, design, failure, steam turbine, stress

Introduction

Electrical power has become an essential facet of life in all spheres of modern society. In the home, electricity is used to power water pumps that provide running water, and heating and air conditioning systems that provide a comfortable atmosphere; electricity is used to power the network of computer systems used extensively in commercial inventory organization, and in the computerized mechanisms that govern manufacturing processes in the manufacturing industry. These are just a few examples that indicate how much modern society relies on electrical power and how important it is to society that a reliable source of electricity be established.

Currently, nearly 90% of the electricity produced in the United States is generated using steam turbines, while about 80% of that produced worldwide comes from steam generators [1]. With such a substantial amount of electrical energy being produced by steam turbine generators, it is in the best interest of society to make these generators as efficient and as sustainable as possible. One of the key factors influencing the efficiency of these turbines is the design of the turbine blades. It was through a century of development and advancement in steam turbine blade design that steam turbine efficiency rose from a mere 60% to 90% or better [2]. Thus, the better the design of the blade, the more efficient the turbine will be; and the more efficient the turbine is, the more efficient the generator is and the better off society is. Therefore, it is beneficial to society to implement advanced blade technology that enhances turbine efficiency.

Blade Materials

The type of material used for turbine blades is based on the stage of the turbine in which the blades will operate. There are three such stages: high-pressure (HP), intermediate-pressure (IP), and low-pressure (LP), which are named according to the relative pressure of the steam in the stage. The pressures and temperatures of each stage limit the kinds of materials that may be used in them. For instance, HP and IP stage blades are generally made from 12Cr martensitic stainless steels [3]. However, blades used in high-temperature (> 450°C) HP or IP applications may be made of austenitic stainless steels because they have better mechanical properties at high temperatures [3]. For example, stainless steel type AISI 422 (a martensitic stainless steel) is commonly used for HP and IP turbine sections, while AISI series 300 steels (austenitic) are used for high-temperature applications [3]. LP blades are often, but not exclusively, made from 12Cr stainless steels also. Common types of stainless steel used in LP sections include AISI types 403, 410, 410-Cb, and 630; the exact type of steel chosen for a particular LP application depends on the strength and corrosion resistance required. Since the 1960s, titanium alloys, especially Ti-6Al-4V, have also been used for LP turbine stages [3]. These alloys are particularly suited to LP stages for a number of reasons. First, the densities of titanium alloys are generally less than the density of steels; for example, Ti-6Al-4V has a density of only 4.43 g/cc while stainless steel type AISI 410S has a density of 7.8 g/cc [4, 5]. This lower density makes it possible to lengthen the LP blades and thereby increase turbine efficiency without increasing stresses in the blades due to centrifugal forces. Second, titanium alloys have greater corrosion resistance than steels; this makes titanium alloys ideal for use in LP stages where there are greater levels of moisture. Finally, titanium alloys are resistant enough to water droplet erosion
that they can be used without erosion protection in certain applications.

Overall, it is the material properties that make a blade reliable or doomed to failure. The yield strength, tensile strength, corrosion resistance, and modulus of elasticity all play a role in determining whether or not a blade will fail under operating loads.

**BLADE LOADING**

Steam turbines operate at similar speeds, usually in the range of 3000-3600 rpm for fossil-fired plants and 1500-1800 rpm for nuclear-powered plants [3]. Because the speeds are similar, the stresses in the turbine blades, which arise because of their movement, are also similar. There are two main categories of stress that the blades experience: static stresses, consisting of centrifugal tensile stresses, centrifugal bending stresses, and steam bending loads, and dynamic stresses, arising from non-uniform steam flows and synchronous resonance of the blade with the operating speed of the turbine. However, the majority of blade stresses are due to centrifugal forces [3].

**Centrifugal Tensile Stress**

Centrifugal tensile stress is the tensile stress induced in the blade as a result of its rotational movement. According to McCloskey [3], the magnitudes of these stresses are proportional to the square of the speed:

$$\sigma_{ct} = (\omega_{cp}/\omega_{100})^2 \sigma_{100ct}$$

where $\sigma_{ct}$ is the centrifugal tensile load, $\omega_{cp}$ is the rotational speed of the blade, $\omega_{100}$ is the design rotational speed, and $\sigma_{100ct}$ is the centrifugal tensile stress in the blade at the design rotational speed. However, blades in the HP and IP stages are shorter than blades in the LP stage; therefore, the centrifugal stresses in the HP and IP stages are relatively small. Centrifugal forces have a greater effect on the LP stage blades due to the longer blade length. According to McCloskey, the steady-stresses in the last-row LP blades are typically 0.5$\sigma_{t}$ for about 50% of the blade length, and greater than or equal to 0.25$\sigma_{t}$ for 80% of that length, where $\sigma_{t}$ is the yield stress of the material [3].

To clarify the action of centrifugal forces, consider the simple equation for the centrifugal force, $F$, acting on a point mass $m$ that is rotating with an angular velocity $\omega$ in a circular path described by the vector $r$, whose magnitude $r$ equals the radius of the path around a certain fixed point:

$$F = m\omega \times (\omega \times r) \quad [6]$$

The result of the first cross product, $(\omega \times r)$, is a vector in the direction perpendicular to the plane of rotation. The result of the second cross product, $\omega \times (\omega \times r)$, is a vector in the plane of rotation in the direction away from the center of rotation of the mass $m$. The multiplication of $m$ with the second cross product returns a vector whose magnitude is equal to the second cross product multiplied by the scalar $m$ and whose direction is the same as that of the second cross product. This product is equal to the force vector $F$. This indicates that the centrifugal force $F$ acts on the point mass $m$ in a direction radially outward from the center of rotation. Although this equation is reliable only for point masses, it helps to illustrate the fact that centrifugal forces tend to ‘pull’ the objects out of their path of rotation. Figure 1 illustrates this point. If a turbine blade is thought of as a finite collection of point masses, then the previous equation may be applied to each point mass to find the resultant centrifugal force acting on the blade. Thus, the centrifugal force creates an overall tensile stress in the blade by ‘pulling’ on the blade as it rotates [3].

![Fig. 1 Centrifugal Force Illustration](image)

**Centrifugal Bending Stresses**

Centrifugal bending stresses arise if the centers of gravity (centroids) of the blade cross-sectional areas at different heights do not lie in a straight line with the blade root’s center of gravity. Because the centrifugal force acts on the centroid of the area and in a direction radially outward, bending moments are produced where the centroids do not lie on the blade’s center of gravity line. This causes tensile stresses on one side of the blade’s center of gravity line and compressive stresses on the other. However, blade designers have exploited the effects of centrifugal bending to counter the effect of steam bending. For example, if a steam-bending load tends to bend the blade axially in the direction of steam flow, a blade designer can intentionally offset the centroids of the blade areas that lie towards the tip of the blade in the direction of the steam load. The centrifugal force acting on
the centroids would then create a bending moment that tends to bend the blade in the direction opposite that of the steam-bending load [3]. Fig. 2 helps to illustrate this point [3].

![Fig. 2 Steam-Bending and Centrifugal Bending](image)

**Steam Bending Loads**

As the steam flows through the turbine blades, the steam pushes on the blades causing them to bend, thus creating what is known as steam bending. Like centrifugal bending, steam bending causes the blades to be bent lengthwise, creating regions of tensile and compressive stress in the blade. Although the movement of the steam does induce blade bending, the effect of steam bending in moving blades is not as pronounced as the effects of centrifugal forces. In fact, steam-bending stresses are typically only about 10% of the centrifugal stresses [3]. The stationary blades of a reaction turbine are more affected by the moving steam because the force of the steam on the stationary blades tends to move the blades in the direction of the force. Because the blades cannot be displaced by the applied force of the steam, they instead bend in reaction. Steam bending occurs in HP, IP, and LP stages, but it is most pronounced in the HP stage where the pressure difference across the blades is greatest. However, steam bending is also significant in LP stage blades because the LP blades are much longer than HP or IP blades [3].

**Dynamic Stresses**

Dynamic stresses are induced in turbine blades when there is some exciting force that causes the blades to vibrate. Exciting forces can arise from sources of non-uniform flows such as nozzle-wake interactions and structural features that interfere with the steam flow, as well as turbine operating speeds [3]. Blade vibrations lead to fluctuations of stress in the blades, sometimes exceeding the yield strength of the blade material. If the amplitude of the stress fluctuations is small, and the stress does not exceed the yield stress of the material at a given amplitude, the blades experience high-cycle fatigue causing them to fail suddenly after a large number of cycles. Larger amplitudes of stress fluctuations will result in greater stresses in the blades and cause low-cycle fatigue with blade failure occurring only after a relatively small number of cycles. Blade vibrations are most dangerous when the frequency of vibrations coincides with the natural frequency of the blades [3]. When this occurs, the blades resonate and fail from high-cycle fatigue in a short period of time.

**Creep**

Turbine blades are constantly subject to high temperatures, predominantly in the HP and IP stages, which tend to soften the blade material. This, in combination with the centrifugal forces exerted on the blades, serves to deform the blades, and cause creep (the slow and continuous deformation of a material over time) [3, 7]. The rate of material deformation (rate of creep) is highly dependent on both the temperature of the material and the applied stress [7]. This is a particularly dangerous phenomenon because the blades are manufactured according to stringent specifications based on the loading and environment that the blades will operate under. Any change in the geometry of the blade due to creep can result in catastrophic failure due to blade degradation or sudden cracking. This is why it is imperative that the materials chosen for the HP and IP blades retain high yield strengths at elevated temperatures.

The above information applies mostly to reaction turbine blading. Impulse turbines differ from reaction turbines in the way that the blades are moved, which results in different stresses in the different kinds of blades. In a reaction turbine, the steam flows through fixed blades with no pressure drop and then flows through the moving blades that are shaped so as to form nozzles that serve to increase the velocity of the steam as it passes through the rotor and in doing so cause the rotor to turn. In an impulse turbine, the steam is directed onto the rotor blades from fixed nozzles. The steam hits the blade creating an impulse and causing the rotor to turn [8]. However, it must be noted that in practice, there are no pure impulse turbines, but only some considered ‘low-reaction’ turbines [9]. Hence, with the possible exception of steam bending stresses, the stresses found in impulse turbine blades may be assumed to be similar to stresses in reaction turbine blades.

All of the stresses listed above will propagate cracks in the material, if there are any to begin with, or they will tend to form cracks from dislocations in the material if there are no cracks initially present. This is dangerous not only because it damages the structural integrity of the blade, but also because cracks serve as repositories for condensed steam, which can then react with the blade materials and cause corrosion of the blade [10].
BLADE CORROSION

Blade fractures and surface roughness, even on a microscopic scale, provide areas where deposits of “highly concentrated aggressive solutions of admixtures [11]” can be formed. The subsequent reaction of blade materials with these admixtures is extremely detrimental to the blade structure. These reactions propagate cracks by corroding the material around existing cracks and in doing so weaken the blade. In essence, corrosion only occurs because of the presence of blade surface cracks. Furthermore, corrosion is accelerated by impurities in the steam. According to Ryuichiro Ebara, in his paper Corrosion Crack Initiation in 12% Chromium Stainless Steel, over eighty different compounds including oxide, silicate, and sulfide have been found in deposits on turbine blades [12]. These impurities, depending on their nature and concentration, can lead to a drastic decrease in blade fatigue strength. Ebara has shown that NaCl and NaOH are very corrosive compounds and therefore very effective in reducing blade fatigue strength. For example, Ebara showed in his study, that even in small (3%-3x10^-7%) concentrations of NaCl solutions the fatigue strength of steel is greatly (~75%) reduced.

Corrosion is of major concern mostly in the LP stage of the turbine because of the lower temperatures, but it is an issue in any area where there is a phase transition (condensation) of the steam. This is especially harmful during turbine downtime when high-temperature stages of the turbine begin to cool, providing favorable conditions for condensation. When the steam condenses on the blade surface, corrosion pits and dimples are formed. These are particularly harmful to the blade because they serve as stress concentrators. In the presence of normal loading and stress conditions, these concentrators often increase the local stresses to many times the overall stress of the blade [13]. These localized increases in stress provide a means by which dislocations in the material’s crystal structure can be moved, resulting in blade deformation and crack propagation.

Ultimately, stress, fatigue, and corrosion are inherently related: Stress induces dislocation movement in the blade’s crystal structure; fatigue fluctuates the levels of stress in the blade, causing material dislocations to accumulate and form cracks, thereby increasing local stress concentrations; corrosion propagates cracks by reacting with blade material around existing cracks, thus increasing the crack size, spreading the stress concentrations, and lessening the blade’s overall strength [13]. Under constant cyclical loading, these three factors combine to cause blade failure. For example, a blade experiencing cyclic loading and centrifugal force F, will have a stress of $\sigma_{tot}$ equal to the sum of all the stresses (centrifugal, centrifugal-bending, steam-bending, and dynamic stresses) acting on the blade. The stress $\sigma_{tot}$ will tend to move dislocations in the material in the same direction. As the number of cycles increase, more and more dislocations are moved, and eventually a crack forms as the dislocations reach the surface of the blade. This newly formed surface crack provides an area for condensed steam to accumulate and a place for impurities carried by the steam to concentrate. The concentration of impurities, if high enough, will corrode the material, thereby lessening the contiguous area of the blade. This will not only weaken the overall strength of the blade, but it will also increase the local stresses at the edge of the crack, thus propagating the crack even further and presenting new areas for corrosion. Eventually, if the crack grows to a critical size, the blade will split at the crack location and fail. This example illustrates the interconnectedness of stress, corrosion, and fatigue, and indicates that the effects of crack and defect accumulation are not insignificant.

ACCUMULATION FAILURES

Over the course of a turbine’s active lifetime, the cyclic loading experienced by its components will build up areas of defects that can severely affect the integrity of the components. Such accumulations of defects increase the possibility of component failure and, if accumulation of defects occurs rapidly, the operating lifetime of the turbine will be significantly shortened. A peer-reviewed case study describes the failure of an 8.25-MW capacity steam turbine [14]. Although the turbine was designed to operate for years, it failed within three months of operation. A thorough examination of the turbine components revealed the presence of “macropores and extended cavities having branched cracks at their ends [14],” as well as a build up of salt deposits in these cavities. From this investigation, the cause of failure was surmised to be a combination of corrosion, from the concentration of salt in the macropores, and stress corrosion cracking due to the concentration of stress in the blade defects. In order to increase the reliability of turbine components, this study recommended that the steam be regulated to ensure a minimum level of impurities, especially chlorides, and that the manufacturing process be improved to reduce macroporosities, segregate microporosities, and increase micro-structure uniformity throughout the material.

Such catastrophes as this indicate the necessity of improved component designs to ensure component reliability and improve turbine efficiency.

BLADE DESIGN

Based on the information provided in the previous sections, an efficient and reliable blade design will satisfy the following requirements:

1. The blade material must have a sufficient yield strength to resist plastic deformation, and must be able to retain such yield strength, or at least most of it, at elevated temperatures.
2. The blade material must be able to be processed and worked with easily (this is one of the
downsides of Titanium alloys as they are not easily welded and they are expensive to produce).

3. Blade materials must exhibit a moderate elastic modulus so that the blade neither deforms exceedingly nor breaks suddenly under normal operating stresses.

4. Preferably, blade materials should be low-density in order to decrease the centrifugal forces, and therefore centrifugal stresses, on the blades.

5. The blades must be corrosion-resistant, even in the presence of aggressive ionic solutions formed by impurities in the steam.

6. Blades must be manufactured in such a way as to minimize initiation of cracks during the manufacturing process.

Kiyoshi Segawa, et al, have developed a new rotor blade for steam turbine plants [15]. The new blade design optimized blade aerodynamics near the root section of the blade, thus decreasing both endwall and profile losses. Based on the results of 3-D stage and air turbine tests, the new rotor blade was found to increase stage efficiency by about 0.3%. In addition, the new blade design was found to improve internal efficiency and reduce manufacturing costs by reducing the blade number by 15% [15].

Walker and Hesketh have determined that improvements in efficiency can be realized by the optimization of aerodynamic parameters including stage heat-drop, blade velocity distribution, surface finish, and three-dimensional design [9]. However, in order to optimize these parameters the constraints imposed by manufacturing costs and mechanical limitations must be considered. For example, reduction of blade stress can be realized with the implementation of lighter-weight materials, such as Titanium alloys. However, such alloys are not suitable for use in regions of elevated temperatures and they are neither easily nor cheaply manufactured. Thus, in order to improve turbine efficiency, a happy medium between cost and performance must be established.

A new blade design developed by Hideo Nomoto, et al, allows steam turbine blades to be more resistant to temperatures up to six hundred and thirty degrees Celsius [16]. Thanks to advancements in computer fluid dynamics, blade design has allowed for a more efficient steam path. The blade is now designed to optimize root and tip area, which in turn minimizes leakage from the steam path to the blade. This allows for a more efficient system where steam is not lost throughout. The introduction of integral snubbing at the tip connects the blades circularly. This new blade design aspect also reduces leakage, as well as vibration control. Both add to the efficiency of the steam turbine system. This new blade design reduces the impact of thermal stress because of the improved efficiency of the system [16].

Effective corrosion resistance is key in improving blade design. Although the materials currently used in turbine blades have some degree of corrosion resistance, the presence or formation of cracks that allow corrosion is practically inevitable. To this end, studies have been conducted to determine whether certain chemical coatings, when deposited on turbine blades, are effective in preventing blade corrosion [17]. E. K. Sevidova, et al, determined that among three coatings (Ti+TiN, Cr+CrN, Cr+(CrTi)N) tested on 20X13 steel, the Cr+CrN coating proved to be most effective in resisting corrosion when exposed to a 3% NaCl solution [17].

Water droplet erosion is also an issue in steam turbines. Erosion of blade materials will distort the geometry of the blade and cause a decrease in efficiency due to aerodynamic losses. In order to improve erosion resistance, coatings that harden the surface of the blade have been investigated. Shun-sen Wang, et al, tested five different boride coatings, three ion-plating CrN coatings, and three thermal-spray coatings on five different substrate steels [18]. They concluded that the thermal coatings had negligible effects on protecting the blade substrate from erosion when compared to the other coatings tested; that the protective coating must be at least equal to some minimum critical value in order to effectively protect the substrate from erosion; that improving coating thickness reduces the erosion rate of the coating; and that the erosion resistance of the coating is strongly dependent on temperature.

Overall, an improved blade design consisting of strong, erosion and corrosion-resistant materials with optimized aerodynamic parameters will result in a more efficient turbine.

**Turbine Efficiency**

Turbine efficiency is lost through defects accumulating in turbine components. As the turbine blades significantly impact the overall efficiency of the turbine [2], defects that accumulate in these components dramatically reduce the efficiency of the turbine. At the worst, these defects can cause the failure of the turbine and necessitate the shutdown of the generator; at best, these defects will increase turbine maintenance costs. When defects arise, such as blade cracking and blade corrosion, the aerodynamic designs of the blades are severely compromised leading to inefficient interactions between the steam and the blades. This consequently increases the amount of fuel consumed to produce the steam, which increases operating costs, which ultimately reflects increased the costs to the consumer. Hence, to avoid, or at least diminish, elevated energy costs, the implementation of an improved blade design in existing turbines, consistent with the findings of this paper, should be considered.

An increase in fuel consumption necessarily increases the amount of emissions from the generator plant. In the case of fossil fuel-burning power plants, this indicates elevated amounts of carbon dioxide emissions. However, improved turbine technologies that utilize cleaner, renewable fuels have been developed, thereby lessening unwanted emissions.
TURBINE SUSTAINABILITY

Sustainability, the ability of a technology to perform while conserving natural resources and having no significant adverse environmental impact, has become a major concern as reserves of fossil fuels (on which modern society heavily relies) begin to fall. Steam turbines have become a very sustainable technology due to advances in cogeneration and renewable fuel technologies. Cogeneration, “the sequential generation of two different forms of useful energy, typically mechanical and thermal, from a single fuel input,” [19] has been utilized by various manufacturing industries across the globe [19]. This utilization not only reduces operating costs due to smaller amounts of electricity consumed by the manufacturer from the grid, but it also lessens the manufacturer’s impact on the environment. Coupled with the use of renewable fuels, cogeneration provides an even more sustainable technology, sometimes with additional benefits over and above a smaller environmental impact. For example, M. A. Mujeebu, et al, conducted a case study on the utilization of a rice paddy husk-fueled cogeneration system in a South Indian rice mill [19]. It was found that if such a system were implemented rice production would increase by at least 30 tons per day and that the system could yield an annual savings of $0.12 million [19]. Aside form the immediate monetary and manufacturing benefits of this system, additional benefits could be gained from the burning of the husk. As the content of the husk is mostly (91%) silica, “amorphous silica can be retained if the burnt husk is heated up to 700 °C [19].” From this, pure silicon, which is used extensively in computer chips and other electronic devices, can be obtained. Additionally, sodium and potassium silicate, used in adhesive and detergent applications, and furfural, used in pharmaceutical products, can be obtained from burnt husk. Moreover, it was found that 1 kg of paddy husk could produce the equivalent energy of “1.5 kg of coal and 1.0 kg of oil [19].” This example serves to show that steam-powered generators, whether they are used industrially or commercially, can be classified as some of the most sustainable energy-generating technologies.

The combination of the two technologies (renewable fuels and improved turbine blade design) presents a notably efficient and sustainable method of generating electrical energy. An improved blade design, focused on resisting the effects of stresses, corrosive agents, and creep-inducing temperatures, will elevate the turbine efficiency, consequently leading to an increase in the power plant’s overall efficiency, a reduction of the amount of fuel consumed, and ultimately a decrease in operating costs. The use of renewable fuels, such as waste, in addition to a more efficient blade design, will serve to reduce operating costs even further and lessen the environmental impacts of steam turbines. Overall, such a combination of technologies would benefit society by providing an efficient, viable, and sustainable means of generating electrical energy.

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ADDITIONAL RESOURCES


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ACKNOWLEDGEMENTS

We would like to thank Lauren Schmeer from the writing center, the staff members at the Hillman Library, and friend Austin O’Keane who have all helped us in our research and composition of this paper.