Modelling and Analysis on the Fatigue Life of Gas Turbine Compressor Disc

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Abstract. The disc itself revolves at an extremely rapid pace, putting a lot of strain on the turbine compressor disc. This exceptionally stressed part provides an impact on a particular location such as a bore, bolt hole, slot, or fillet. The bore area of the disc is an especially crucial zone, since any failure there would result in an unprecedented breakdown of the entire turbine. So in this study, the finite-element approach is employed to offer a numerical estimate of the lifespan of a gas turbine prototype disc. Engine start-up and shutdown, as well as significant throttle fluctuations during operation, can cause cyclic tensile stresses in this area. These cyclic tensile stresses will surpass the component's yield strength and may potentially induce low cycle fatigue failure. As a result, there is a need to improve the fatigue and fracture lifetime of the bore area in order to meet the expanding design life requirements.

1 Introduction

Aero engine specifications demand more power, fewer pounds, and fewer expenses while preserving flight safety and engine efficiency. This implies fewer, heavier-loaded compressor and turbine phases operating at greater temperatures [1].

Some of the more costly elements are gas-turbine discs that function in the overheated area of the engine. As a result, significant study is being conducted in this field to decrease prices, strengthen materials, create thermomechanical interventions, and maximize device lifespan [2, 3]. The principal operation of the turbine is to get energy from the hot gas and this energy helps to drive the compressor. The turbine disc is subjected to high rotational speeds and centrifugal forces which produces extreme temperatures which negatively affect the strength of the material. The role of the discs is to locate the ring of the rotating blades inside the engine and transmit the energy absorbed by them through the shafts connecting the turbine to the compressor. The turbine disc which is the most critical part of the component, should withstand substantial mechanical and thermal loading. If any difficulty arises in the turbine section it will considerably affect the total engine performance [1, 4, 5].

Mostly in compressors, it's common to have pressure ratios to vary within 17 to 20, with some units having pressure ratios up to 30:1 [6]. The pressure ratios are increased for pursuing higher efficiencies. Compressor disc is subjected to higher rotational speeds and therefore higher loads causing the bore region of the disc to experience higher loads. Corrosion cracking, resonance and low cycle fatigue tends to crack or rupture the rotor disc.

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causing it to fail frequently. The other being the rotor burst is caused due to whirl unbalance, alignment errors, low cycle fatigue [7, 8].

Few technologies viz., life prediction, fracture mechanics, non-destructive evaluation, etc. have been used to overcome the failure in the disc component. With the help of these techniques, the components are inspected for specific crack sizes which degrades the life of an engine component. The elements lifespan are also predicted using these techniques. However in the crack initiation criterion if the crack is detected before the element retirement lifespan, then the element is retired instantly. Shot Peening method is used to retard the crack growth in specified locations of an engine. Shot-peening introduces vital near surface compressive stresses. These residual compressive stresses help in enhancing fatigue life, retardation of crack growth and resistance to foreign object injuries [9, 10].

Due to the compressive stresses, life of the engine components increase. A technique called auto-frettage, helps in inducing compressive pre-stresses in components subjected to reduce tensile stress and also aids in enhancing fatigue life of components [11]. In pre-spin approach disc is spun to a speed that's sufficiently high to deform the bore region on the far side of yield point. Unloading in the bore region causes residual compressive stresses, which is done by stopping of the disc. Due to continuous operation of turbine the compressive residual stresses reduces the tensile stresses created by operational load. Reduction in tensile stresses leads to increased lifetime of the disc [12, 13].

A metal subjected to a repetitive or unsteady stress can fail at a stress, less than that needed to cause failure on application of load. Failures occurring below conditions of dynamic loading area unit is known as fatigue failure. Fatigue failure is characterized in 3 phases- crack initiation, crack propagation and final fracture. So, it is feasible to acquire excellent options of expected lifespan by testing materials with geometrical and mechanical qualities comparable to key portions of discs and utilizing variables derived from finite element (FE) analysis, coupled with relevant information. The time and expenses related to production will be decreased using findings derived for disc geometries using the FE approach and characteristics based on actual data. The mechanical properties of AISI 4340 is described in Table 1. After applying the above material, the fatigue analysis was performed to quantify whether the above used material is fit for the disc or not

<table>
<thead>
<tr>
<th>Table 1. Mechanical characteristics of AISI 4340 alloy steel</th>
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<tr>
<td>Ultimate tensile stress</td>
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<tr>
<td>Tensile yield strength</td>
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<tr>
<td>Modulus of elasticity</td>
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<td>Poisson’s ratio</td>
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2 Analysis of a model disc following the FE approach

To prevent rigid body motion, a constraint was applied to one of the bore edges. A rotational disc was introduced to impose a load on the disc, ensuring stability. The model of the compressor disc, incorporating the mass of the blades, is depicted in Figure 1. The entire design of the compressor disc was meticulously modelled using SOLIDWORKS software, providing a comprehensive representation of the structural elements and their interactions. This integrated approach in design not only enhances the accuracy of the model but also facilitates a more realistic simulation of the compressor disc's behaviour under various conditions.
Central to the analysis is the assumption that crack propagation follows a 2D configuration at the center of the disc, a simplification adopted for a more straightforward evaluation of crack growth. This assumption is based on the acknowledgment that tangential stresses play a significant role in influencing crack development. To delve into crack growth dynamics, a 2D plane is employed to model the cracked configuration. This approach allows for a focused exploration of the factors influencing crack expansion, particularly the role of hoop stresses in attempting to propagate and open the crack.

By adopting a 2D perspective, the analysis aims to capture the critical mechanisms governing crack growth, emphasizing the tangential and hoop stresses that contribute to the evolution of the crack. This methodological choice not only streamlines the analytical process
but also enables a detailed examination of the interplay between stresses and crack propagation, offering insights into the structural behaviour of the disc under the influence of different loading conditions. The 2D model provides a valuable platform for studying the intricate dynamics of crack growth in the disc, shedding light on the underlying factors that influence its structural integrity [14].

The fatigue analysis was precisely conducted using SOLIDWORKS simulation. The initial phase involved a comprehensive static analysis of the model. Subsequently, the disc underwent a meshing process, ensuring that all pertinent constraints were duly considered and incorporated as outlined in Table 2. This step-by-step approach in the analysis provides a robust foundation, starting with a static evaluation that allows for a detailed understanding of the disc's structural response. The subsequent meshing process is crucial for capturing the intricacies of the disc's geometry and material behaviour, setting the stage for a thorough fatigue analysis. The inclusion of constraints, as documented in Table 2, ensures a correct representation of the real-time conditions, enabling a reliable and accurate assessment of the disc's fatigue performance. Through the integration of SOLIDWORKS 2013 simulation capabilities, this analysis aims to offer valuable insights into the fatigue life and structural integrity of the disc under varying operational conditions. Subsequently, the compressor disc was secured at the center, and the specified forces were then applied, as detailed in Table 3.

<table>
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<th>Table 2. Detailing of mesh</th>
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<tr>
<td><strong>Total Nodes</strong></td>
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<td><strong>Total elements</strong></td>
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<tr>
<td><strong>Maximum Aspect ratio</strong></td>
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<td>% of elements with Aspect Ratio &lt; 3</td>
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<tr>
<td>% of elements with Aspect Ratio &gt; 10</td>
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</table>

4 Results and discussions

4.1 Static analysis

The disc undergoes a maximum stress of 394.56 MPa, and concurrently, experiences a resultant displacement measuring 0.0957508 mm. The outcomes derived from the static analysis of the system are detailed as shown in figure 3. The maximum stress and displacement in a disc, as reported in a static analysis, are influenced by various factors. The stress distribution in a rotating disc with variable thickness is affected by the loadings, with the maximum radial stress occurring in the thinnest area [15, 16]. In a partially loaded hollow disc, the maximum tensile stress can be almost twice the internal pressure, while the maximum compressive stress is not greater than the applied internal pressure [17, 18].
4.2 Fatigue analysis

Subjecting the disc to fatigue loading, an investigation was conducted to determine the point at which the disc fails after a specific number of revolutions. Applying a fatigue load equivalent to 5 million revolutions, the analysis revealed that the maximum damage incurred during this loading condition amounted to $2.378 \times 10^5$, and the corresponding maximum life of the disc was determined to be $10^6$ cycles. This information sheds light on the disc's performance under prolonged cyclic loading and provides insights into its durability and structural integrity over an extended period of operation. A range of studies have explored the complex issue of fatigue damage in various loading conditions. Chen et al. found that circular strain paths resulted in the greatest damage and shortest fatigue life, highlighting the importance of considering fatigue failure mechanisms [19]. Han et al. proposed methods for assessing fatigue damage under combined high and low cycle loading, which can significantly reduce the life of structures [20].
5 Conclusions

The aforementioned investigation highlights that when a compressor disc, constructed from AISI 4340 alloy steel, is exposed to substantial loads over a cyclic loading regime of \(5 \times 10^6\) cycles, there is no evidence of crack initiation or structural damage. This observation implies that the AISI 4340 alloy steel exhibits a notable resistance to fatigue failure within this specific operating condition. Consequently, based on the study results, it can be concluded that AISI 4340 alloy steel is deemed safe and reliable in the fatigue zone characterized by \(5 \times 10^6\) loading cycles. The absence of crack initiation or damage underscores the material's durability and structural integrity under the specified high-load cyclic conditions, thereby affirming its suitability for application in such scenarios.

References

11. M. H., Bell, Spin test of turbine rotor (1972) NPS-57VA71061B.