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Studying the Effect of Elastoviscoplastic Modeling on Burst Speed Margins of Turbine Disc

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Abstract: Aero engine turbine discs are critical components that can shatter owing to excessive mechanical loads during operation, endangering aircraft safety. Understanding burst speed margins, the buffer between maximum and actual rotational speeds, is essential for ensuring safety. ANSYS APDL software is used to examine a 2D axisymmetric non-uniform turbine disc utilizing INCONEL 718 and Ti-6Al-4V materials and numerous models. This research, which includes centrifugal, gas, and thermal loads, accurately predicts burst speed and confirms linear elastic analysis. For elastic-plastic analysis, Robinson's criterion is utilized, Perzyna for elastoviscoplastic behavior, and Bilinear isotropic hardening for elastic-plastic behavior. A sensitivity analysis of Perzyna model parameters reveals that elastoviscoplastic analysis yields higher burst margins than elastic-plastic analysis for this turbine disc. The parameters are calibrated using existing models from the Literature.
Keywords: Turbine disc, Inconel 718, Ti-6Al-4V, Elastoviscoplastic and Perzyna.

I. INTRODUCTION

Turbines hold a pivotal role in the field of engineering and power generation by harnessing energy from diverse sources and converting it into valuable mechanical work. These versatile machines find application in a wide array of settings, from powering industrial processes to propelling aircraft. At the heart of these turbines lie the turbine discs, meticulously engineered components designed to bear the brunt of immense mechanical loads and formidable rotational forces. The turbine disc used in the turbojet engines is shown in the figure.

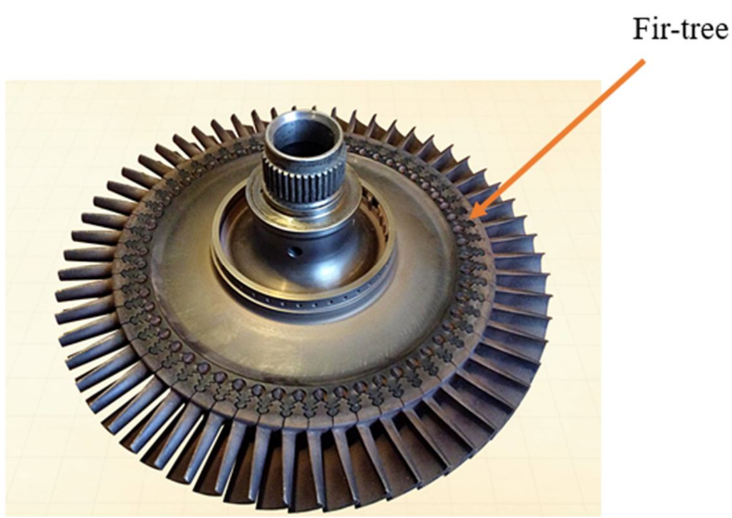

Figure 1: Turbine disc with fir-tree fixture

Yet, amidst the impressive functionality of turbines, a lurking peril emerges in the form of overspeed – a scenario in which the turbine's rotational velocity exceeds its meticulously prescribed operational limits. Overspeed, if left unchecked, can unleash catastrophic consequences, none more ominous than the dreaded "turbine disc overspeed burst."


Figure 2: Burst fragments of turbine disc

This burst constitutes a grave and potentially hazardous eventuality, characterized by the turbine disc's rotational speed breaching its maximum safe operational threshold. A multitude of factors, ranging from abrupt load variations to control system anomalies and mechanical irregularities, can conspire to push the turbine disc into this treacherous territory.

The aftermath of a turbine disc overspeed burst paints a grim picture. The relentless rotational forces exerted upon the disc can propel it past the limits of its material strength, resulting in mechanical failure of dire proportions. In the wake of such a burst, the disc may fissure, rupture, or fragment, imperiling not only the integrity of the turbine itself but also posing a formidable risk to surrounding equipment and the safety of personnel. To mitigate the looming specter of turbine disc overspeed bursts and ensure a climate of secure and dependable operation, meticulous turbine design and comprehensive analysis are imperative. Engineers wield an arsenal of finite element tools (FEA) to dissect the behavior and vulnerabilities of these critical components, enhancing their understanding and predictive capabilities. The gravity of turbine disc failure extends beyond safety considerations; it exacts a significant toll on the economic landscape. Consequently, the imperative to comprehend, predict, and mitigate the risks associated with turbine disc overspeed bursts transcends engineering pursuit, emerging as a safeguard against both perils and financial repercussions. Depending primarily on elastic-plastic analysis falls short of the mark in the search of precise and dependable burst speed assessment for turbine discs. To provide a full assessment of burst speeds, elastoviscoplastic analysis must be performed. This more complex methodology not only improves our understanding but also our capacity to foresee and anticipate crucial failure sites, assuring the highest level of safety and integrity in turbine operations.

II. LITERATURE REVIEW

Researchers and engineers have worked hard over the years to examine the burst speed margin of elastic, elastic-plastic, and elastoviscoplastic turbine discs. Numerous studies have investigated various theoretical, experimental, and computational techniques for precisely and effectively assessing the burst speed margin.

A series of studies in the field of turbine disc research have provided useful insights into overspeed burst analysis. Mazière et al. [1] used experimental and finite element approaches to explore spinning disk overspeed bursts, and found significant agreement between numerical and experimental results. In later work [2,] they investigated elastoviscoplastic rotating disks, emphasizing the impact of material characteristics on disk stability, notably the significance of material viscosity.

Ranjan Kumar et al. [3] assessed the burst margin of gas turbine discs using finite element modeling, indicating the sensitivity of the burst margin to rotational speeds and the benefits of variable thickness discs. Nicola Squarcella et al. [4] demonstrated the greater accuracy of Robinson's semi-empirical technique over finite element analysis for burst speed prediction.

Maruthi B.H. et al. [5] concentrated on aero-engine discs, using finite element modelling to estimate overspeed and burst margin limitations at different temperatures, emphasizing the importance of tangential stress components in changeable temperature scenarios.

Hojjati et al. [6] investigated non-uniform thickness and density rotating discs and found that the VMP approach and finite element analysis findings agreed quite well. Lakshman Kasina et al. [7] carried out a computational study to estimate stresses and optimize turbine disc designs for weight reduction. Their findings highlighted the significance of bore width, bore radius, bore height, web width, and neck width in shaping burst margins and disc stress distributions. These research, taken together, add to our understanding of turbine disc behavior and safety.

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A.K. Asraff et al. [8] investigated the viscoplastic characteristics of high-temperature Austenitic Stainless Steel. Using an INSTRON 8862 electromechanical UTM, they calibrated the Perzyna model parameters via tension tests and the Chaboche and Voce model parameters using low-cycle fatigue testing at 1000 K. The Perzyna model parameters were validated by comparing tension test results to finite element simulations performed with ANSYS (Version 16.0) software. They also performed a viscoplastic cycle stress analysis on a double-walled rocket engine thrust chamber, demonstrating the material's higher dynamic yield strength due to strain rate effects in both experimental and numerical data. A combination of Perzyna and the MISO model produced positive results when modelling monotonic loads. The Perzyna model, in conjunction with Chaboche's nonlinear kinematic hardening model and Voce's nonlinear isotropic hardening model, proved extremely effective in cyclic loading scenarios. The researchers also investigated the sensitivity of Perzyna model parameters'm' and 'D,' discovering that decreasing these parameters intensified rate-dependent effects.

III. SCOPE OF THE STUDY

The study's main goal is to compare the burst speeds obtained from elastic-plastic and elastoviscoplastic analysis of a 2D axisymmetric turbine disc subjected to complex loading (gas, thermal, and centrifugal loading) using a finite element tool, and to show the accurate results of the burst margins. Also, conduct a sensitivity analysis on the influence of Perzyna model parameters on burst margins.

A. Parametric Model

The geometry of the turbine disc model was obtained from the public domain. For the modeling, a turbine disk model generated from a turbine assembly of a legacy engine is used. The figure depicts the geometry of the turbine disc.

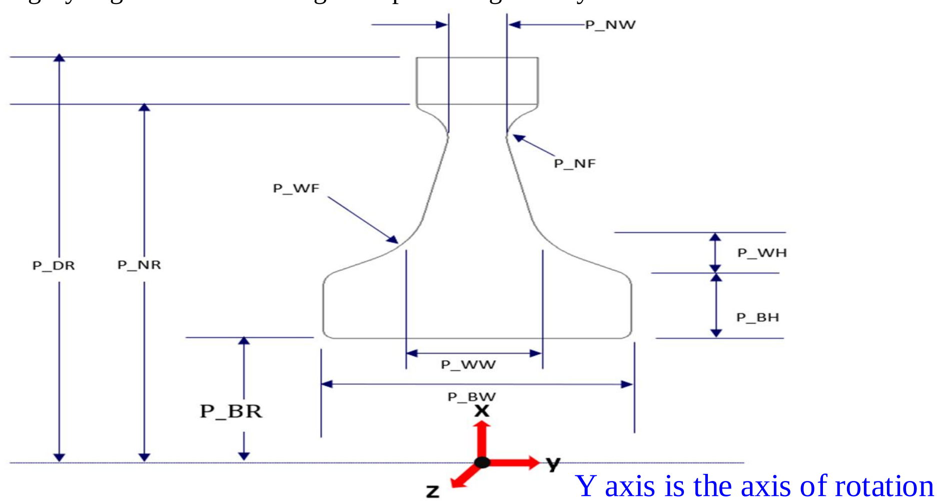

Figure 3: Geometry of the model

Table 1: Dimensions of the disc

Parameter	Description	Baseline (in)
P_BW	Bore Width	6
P_BR	Bore Radius	4
P_BH	Bore Height	2
P_WW	Web Width	2.5
P_WH	Web Height	1
P_WF	Web Fillet	2
P_NW	Neck Width	1.25
P_NF	Neck Fillet	1
P_NR	Neck Radius	11.5
P_DR	Dead Rim Radius	13

The table shows the dimensions of the turbine disc's bore, web, and rim. The 2D turbine disc model is generated using these dimensions in any of the design modeling softwares or design modeler in the ANSYS software itself.

B. Finite Element Model

The turbine disc is represented by a 2D axisymmetric turbine disc model. For the modeling, a PLANE 182 element is used to simulate the disc, and the turbine disc's behavior is considered to be axisymmetric. ANSYS APDL software is used for model modeling and analysis. The Finite element model of the turbine disc is depicted in the figure below.

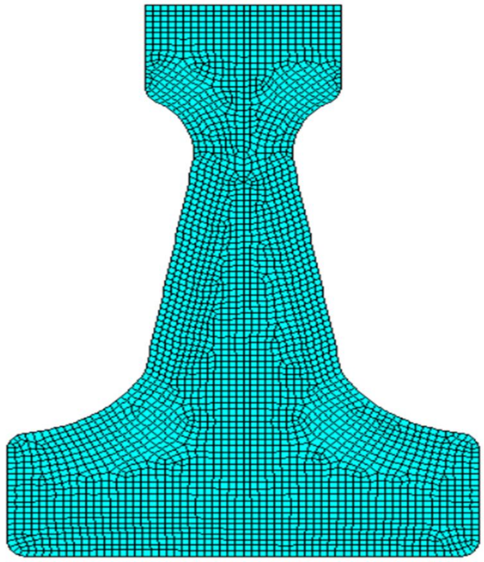

Figure 4: FE model of the turbine disc

To avoid stiff body motion, a node near the bore center is limited in the axial direction. Blade assembly is simulated using MASS 21 elements. For applying aero stresses from blades, the MASS 21 element is modeled at the center of pressure. The mass element is given as 1e-6 with negligible mass. In ANSYS, the Couple equations option is used to connect the Mass element node to the extreme nodes at the rim section. The turbine disc is subjected to a variety of loading conditions, including centrifugal, gas, and thermal loads. The maximum aerodynamic load on the disk is 4000 lbs. In the direction of rotation, the disc is subjected to a maximum speed of 15000rpm. And this speed is rapidly increased in order to determine the turbine disc's burst speeds. Temperatures of 800ºF and 1200ºF were applied to the bore and rim regions of the turbine disc, resulting in thermal loads in the turbine disc. The FE model with all boundary conditions and thermal mapping is shown in the figure below.

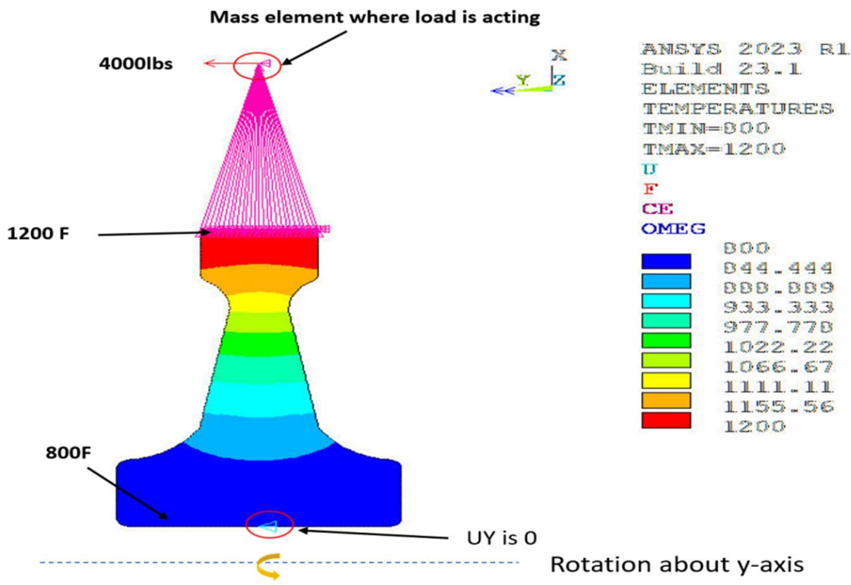

Figure 5: Turbine disc with all boundary conditions

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IV. MATERIAL PROPERTIES

The disc is made of INCONEL 718 and Ti-6Al-4V materials. The material properties of the turbine disc at 800ºF and 1200ºF temperatures are shown in the below tables.

Table 2: INCONEL718 properties

	70 F	1200 F
Density	0.296 lb/cu.in	0.296 lb/cu.in
Young's Modulus	29 E3 ksi	23.7 E3 ksi
Poisson's Ratio	0.3	0.3
Tensile Strength, Yield	150 ksi	125 ksi
Tensile Strength, Ultimate	185 ksi	145 ksi
Coeff Thermal Expansion	0.00000731 in/in/ºF	0.00000839 in/in/ºF

Table 3: Ti-6Al-4V properties

	70 F	1200 F
Density	0.1597 lb/cu.in	0.15643 lb/cu.in
Young's Modulus	18129.717216 ksi	7977.0755752 ksi
Poisson's Ratio	0.34	0.38
Tensile Strength, Yield	145.04 ksi	43.51 ksi
Tangent Modulus	101.5264 ksi	275.5717 ksi
Coeff Thermal Expansion	0.000004877 in/in/ºF	0.0000064888 in/in/ºF

V. FAILURE CRITERIA

A. *Robinson Criterion*

This is one of the revolving discs' failure criteria. The Average hoop stress criterion is another name for it. The Robinson Criterion is a semi-empiric method for determining burst speed in the hoop mode given ultimate tensile strength, σ_{UTS}, and mean hoop stress, $\sigma_{c,mean}$. "Burst occurs when the mean hoop stress on a disc section equals the nominal tensile strength material, as determined by a uniaxial tensile test," according to the criteria.

The actual maximum speed of the turbine disc is 15000rpm, which is expressed as ω.

Then the mathematical formulation is:

$$\omega_{burst} = \omega \sqrt{\frac{\sigma_{UTS}}{\sigma_{c,mean}}}$$

B. *Burst Speed Margin*

The safety margin or safety factor that is integrated into the design to maintain the structural integrity of the disc during operating conditions is referred to as the burst margin. It is an important measure for determining the disc's capacity to endure mechanical loads and stresses during rotation without failure.

The disk burst margin is expressed as the ratio of strength to the applied load.

Mathematically it is given by equation

$$\text{Burst Margin} = \sqrt{\frac{\textit{Average UTS}}{\textit{Average Hoop Stress}}}$$

VI. CONSTITUTIVE MODELS

A. *Perzyna Model*

A visco-plastic model called the Perzyna model is used to explain how materials that experience both plastic deformation and viscous flow behave. Understanding and predicting the behaviour of materials under complicated loading conditions is a typical application in the domains of material science and solid mechanics, particularly in metal forming processes and high-strain-rate applications.

The fundamental empirical equation of Cowper and Symonds provides the simplest description of dynamic behaviour of a visco-plastic material

$$\frac{\sigma_d}{\sigma_s} = 1 + \left(\frac{\dot{\varepsilon}}{D}\right)^m$$

The Perzyna model is obtained by rearranging the basic Cowper and Symonds equation as follows:

$$\dot{\varepsilon} = D\left(\frac{\sigma_d}{\sigma_s} - 1\right)^{1/m}$$

Where,
$\dot{\varepsilon}$ is the strain rate
σ_d is the rate-dependent or dynamic yield stress,
σ_s is the static yield stress, and
D or γ is material viscosity parameter (has the same units as strain rate)
m is hardening parameter

B. Elastoviscoplastic Model

The mechanical behaviour of materials that exhibit both elastic and plastic deformation as well as time-dependent (viscous) responses is described by elastoviscoplastic constitutive models. These models are especially pertinent for materials like metals, polymers, and specific composites that exhibit behaviour that is rate-dependent.
For an elastoviscoplastic material the stress, after exceeding the yield stress, continues to increase beyond the initial yielding point. This implies that the yield stress in the sliding element increases with strain and the model may be expressed in generic terms as

$$\begin{aligned} \boldsymbol{\varepsilon} &= \boldsymbol{\varepsilon}_{\mathrm{e}} = \mathsf{E}^{-1}\,\boldsymbol{\sigma} = \boldsymbol{\varepsilon} && \text{for } ||\boldsymbol{\sigma}|| < \sigma_y \\ \dot{\boldsymbol{\varepsilon}} &= \dot{\boldsymbol{\varepsilon}}_{\mathrm{e}} + \dot{\boldsymbol{\varepsilon}}_{\mathrm{vp}} = \mathsf{E}^{-1}\,\dot{\boldsymbol{\sigma}} + f(\boldsymbol{\sigma}, \sigma_y, \boldsymbol{\varepsilon}_{\mathrm{vp}})\,\boldsymbol{\sigma} && \text{for } ||\boldsymbol{\sigma}|| \geq \sigma_y \end{aligned}.$$

To investigate elastoviscoplastic behaviour, combine the elastic model with Perzyna of the Visco-plastic models. This model combination provides an accurate forecast of results.

VII. RESULTS

A. Elastic-Plastic Analysis Results

Elastic-plastic analysis is performed for nonlinear situations in which the stress created surpasses the yield stress, resulting in plastic strains. For consideration, elastic-plastic analysis produces better findings than linear elastic analysis. The model is examined for elastic-plastic conditions in order to determine burst speeds in ANSYS APDL and to compare theoretical burst speeds.
Plastic strains are formed by raising the speed of the disc, according to the analysis. The burst speed of the disc at which the solution has not converged is obtained. The solution of the analysis is not converged at 17000rpm, implying that the burst speed of the 2D disc for the INCONEL 718 material is 17000rpm. This is the disc's burst speed when subjected to all thermal, centrifugal, and gas loads. The solution for the burst speed in ANSYS for complex loading is not converged at 17800 rpm for the titanium alloy, i.e., Ti-6Al-4V material as turbine disc. As a result, the turbine disc's burst speed for Ti-6Al-4V material is 17800 rpm.

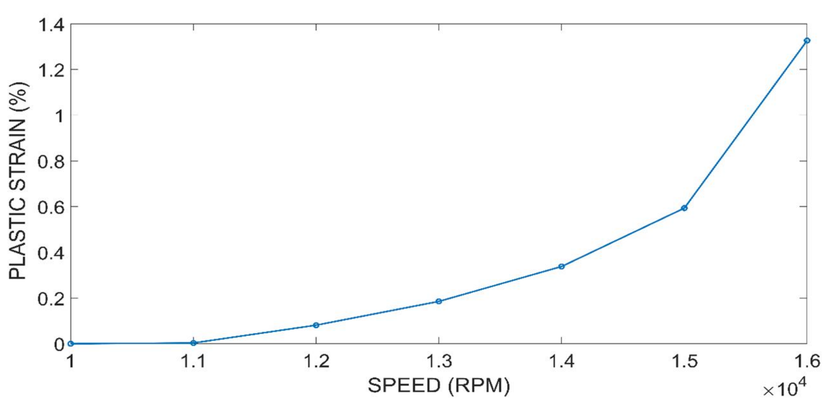

Figure 6: Plastic strain vs. speed for Inconel 718 from elastic-plastic analysis

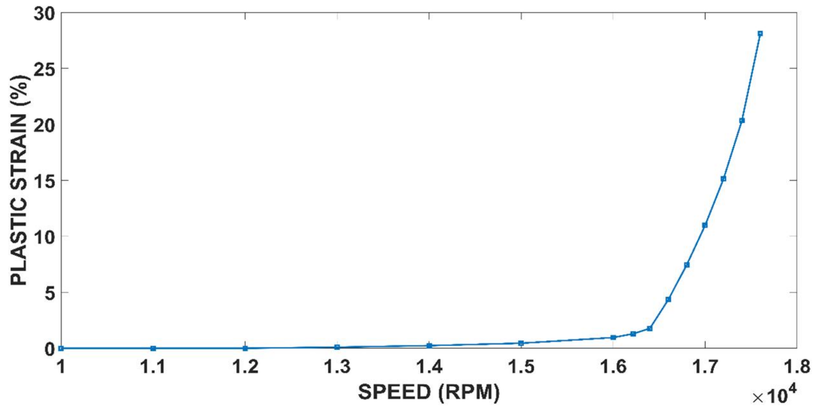

Figure 7: Plastic strain vs. speed for Ti-6Al-4V from elastic-plastic analysis

For complex loading conditions, determining the model's burst speed is difficult. As a result, just the centrifugal load situation is considered for the burst speed analysis simulation, and the burst speed produced from the Robinsons burst speed criteria formula is compared.

Table 3: Comparison of numerical and theoretical burst speeds in RPM

	ANSYS	THEORETICAL
INCONEL 718	17700	16762
Ti-6Al-4V	23500	21707.06

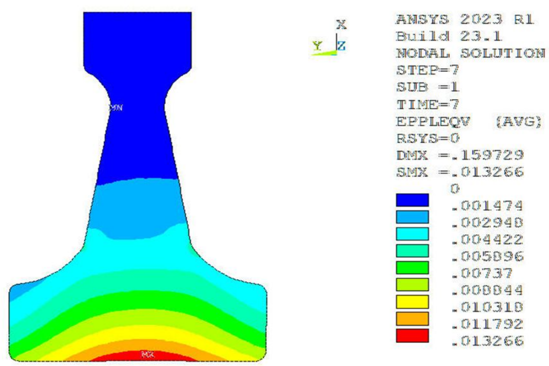

Figure 8: Plastic strain contour plot for Inconel 718 before burst

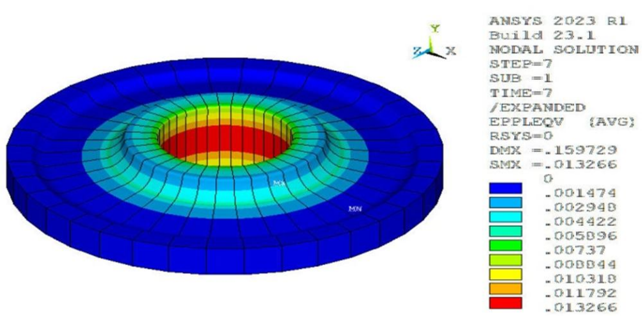

Figure 9: Full expansion of 2D disc contour plot of plastic strain for Inconel 718

The above are the Plastic strain contour plots for 2D turbine disc and Full expansion of Turbine disc For Inconel 718 material.

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B. Elastoviscoplastic Analysis Results

The burst speed in the turbine disc is accurately estimated using elastoviscoplastic analysis. It is a combination of a material's elastic, viscous, and plastic deformation characteristics. This form of analysis is utilized in the examination of turbine discs to investigate the disc material's response to mechanical and thermal loads encountered during operation.

This approach employs a hybrid of elastic and viscoplastic models. Many viscoplastic constitutive models are available for examination, including the Perzyna model, the Anads model, the Chaboche model, and the Johnson-cook model. The Perzyna viscoplastic model is used for simulation in this thesis because it produces faster results than the other models.

The perzyna model is influenced by two variables: the strain rate hardening parameter (m) and the viscous parameter (γ). However, determining these factors is difficult, and more experimental findings are required to assess these parameters. So, in this thesis, a sensitivity study is performed, which provides a clear picture of how the values of burst speed alter by varying the perzyna model parameters.

C. Sensitivity Study of Perzyna Parameters

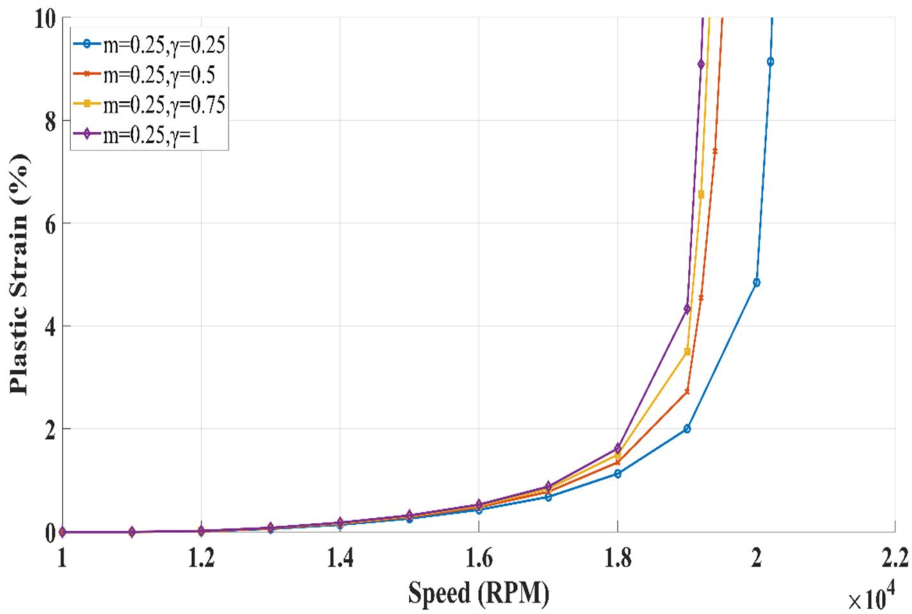

Figure 10: For m = 0.25, Plastic strains vs. Speed for Inconel 718

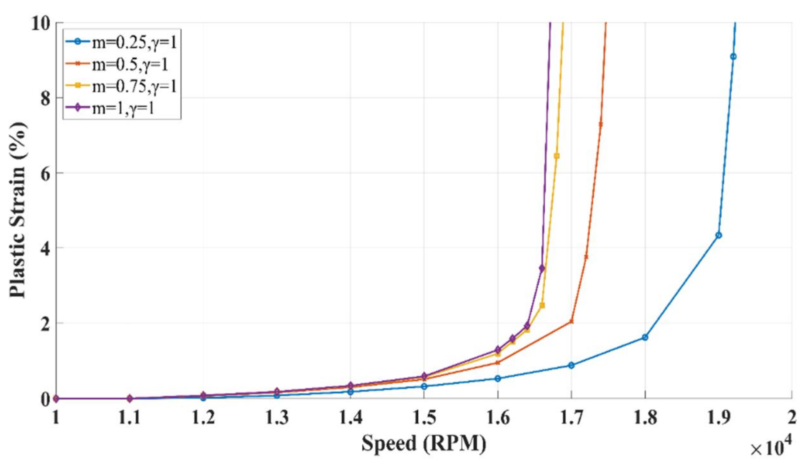

Figure 11: Speed vs. Plastic strains for Inconel 718 by varying Hardening parameters

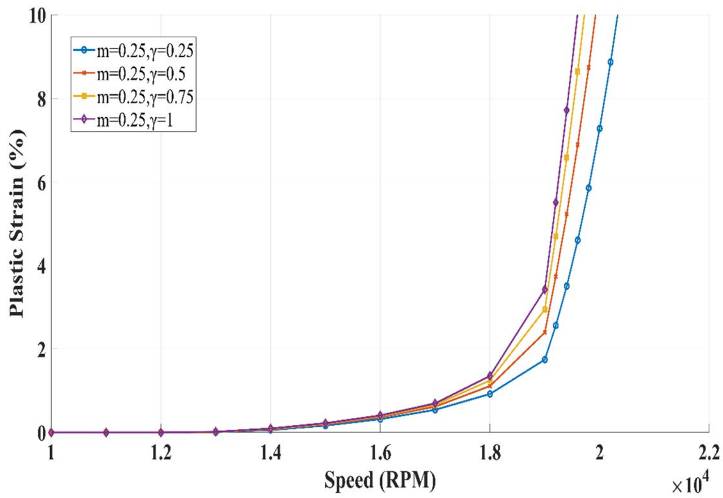

Figure 12: For m = 0.25, Plastic strains vs. Speed for Ti-6Al-4V

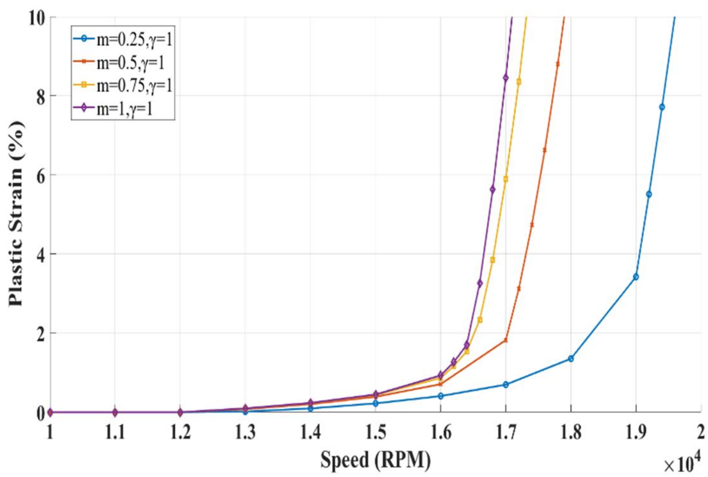

Figure 13: Speed vs. Plastic strains for Ti-6Al-4V by varying Hardening parameters

a) Sensitivity Study on 'm'

The hardening parameter (m) sensitivity analysis is performed on Inconel718 and Ti-6Al-4V alloys. The graphs show that increasing the hardening parameter 'm' increases the plastic strains while keeping the viscous parameters constant. When compared to the viscous parameter 'm,' which has the greatest influence on material behaviour. This parameter has an effect on the burst margins as well. The burst margin grows as the hardening value is reduced from 1 to 0.25.

b) Sensitivity Study on 'γ'

The viscous parameter 'γ' is the material property. When the viscosity parameter is increased, the material becomes more viscous and rate-sensitive. This means that the material will deform and respond more slowly under applied loads. However, based on our data, the hardness parameter has a greater impact than the viscous parameter. That is why plastic strains grow as the viscosity parameter increases. As 'γ' increases from 0.25 to 1, the burst speed margin decreases.

In this work, the burst speeds are estimated using the Perzyna model by adjusting the sensitivity parameters, and the burst speeds vary for different parameters. The hardening and viscous parameters are essential for obtaining accurate results. However, determining these characteristics is quite challenging. It is recommended to conduct experiments on the material to obtain the correct parameters for determining accurate burst speeds.

D. Comparison between Elastic-plastic and Elastoviscoplastic analysis

The burst speeds are obtained for Inconel 718 and Ti-6Al-4V materials using Elastic-plastic and Elastoviscoplastic analysis in ANSYS APDL.

Table 4: Summary of results

	Burst speed (RPM)	
	Inconel 718	Ti-6Al-4V
Elastic-Plastic	17000	17800
Elastoviscoplastic:		
m = 0.25, γ = 1	21000	23200
m = 0.5, γ = 1	20000	21400
m = 0.75, γ = 1	19000	21200
m = 1, γ = 1	19000	20200
m = 0.25, γ = 0.25	21400	24400
m = 0.25, γ = 0.5	20400	23400
m = 0.25, γ = 0.75	21000	23200
m = 0.5, γ = 0.25	21200	24200
m = 0.5, γ = 0.5	21000	23200
m = 0.5, γ = 0.75	20000	22200

According to the table, the burst speeds from the elastoviscoplastic analysis are greater than those from the elastic-plastic analysis for both materials, Inconel 718 and Ti-6Al-4V. As in the case of aero engines, disc failure is catastrophic, and elastic-plastic analysis is sufficient for the study. However, Elastoviscoplastic analysis is recommended for precise estimation of the burst speed margins of the turbine discs.

E. Calibration with Perzyna Parameters from Literature

The perzyna model parameters are extremely difficult to determine. Furthermore, more experimental investigations on the material utilized for the disc at various working circumstances and loading rates are required. A.K. Asraff et al. [11] conducted research on the evaluation of the visco-plastic parameters of an austenitic stainless steel at high temperatures and published data on the calibration of Perzyna model parameters of an austenitic stainless steel from tension testing. A clear approach for determining the perzyna model parameters is described in that literature. By conducting experimental tensile tests on SS-321 material, the parameters hardening parameter 0.412 and viscous parameter 0.322 were acquired from the approach.

These characteristics are taken into account for the turbine disc in this thesis for validation.

The elastic-plastic parameters yield a burst speed of 8000 rpm, whereas the elastoviscoplastic parameters yield a burst speed of 11000 rpm. As a result, the parameters chosen are validated since elastoviscoplastic analysis predicts burst speed greater than elastic-plastic analysis. Therefore, the parameters generated in the literature are then used for the Inconel 718 and Ti-6Al-4V materials of the 2D disc.

Using the perzyna model parameters, the Inconel 718 material model bursts at **22000 rpm**, while the Ti-6Al-4V material model bursts at **25000 rpm**. When these burst speed margins are compared to elastic-plastic analyses, these burst speeds are greater. This investigation concludes that elastoviscoplastic analysis provides higher burst speeds than elastic-plastic analysis. However, calibration of the sensitivity parameters is more important for accurate results.

VIII. CONCLUSIONS

From this in-depth analysis of turbine disc failure behaviour, several significant conclusions can be drawn. These conclusions shed light on the factors contributing to turbine disc failures and provide valuable insights for enhancing the reliability and performance of turbine systems. Through meticulous examination and interpretation of the data, a clearer understanding of the failure mechanisms has emerged, paving the way for informed strategies to mitigate such failures in the future.

1) The nickel-based alloy Inconel 718 and the titanium alloy Ti-6Al-4V materials are utilized for the turbine disc material, and the burst speed margins vary due to differences in densities.

2) The burst speeds predicted from the Robinson's criterion of failure of the turbine disc are quite close to the findings obtained from ANSYS by considering only centrifugal loading because evaluating complex loading for elastic plastic conditions is difficult.
3) Sensitivity analysis is performed for the Perzyna constitutive model parameters in order to gain a better understanding of the Viscoplastic behavior of the turbine disc model, and it is concluded that the Perzyna model parameters have a greater impact on the analysis of burst margins and the increase of hardening parameter, which increases the plastic strains.
4) According to this thesis, the burst speeds obtained from the elastoviscoplastic analysis provide higher burst margins than the elastic-plastic analysis of the turbine disc subjected to centrifugal loading + thermal loading and gas loadings using numerical software.

IX. ACKNOWLEDGMENTS

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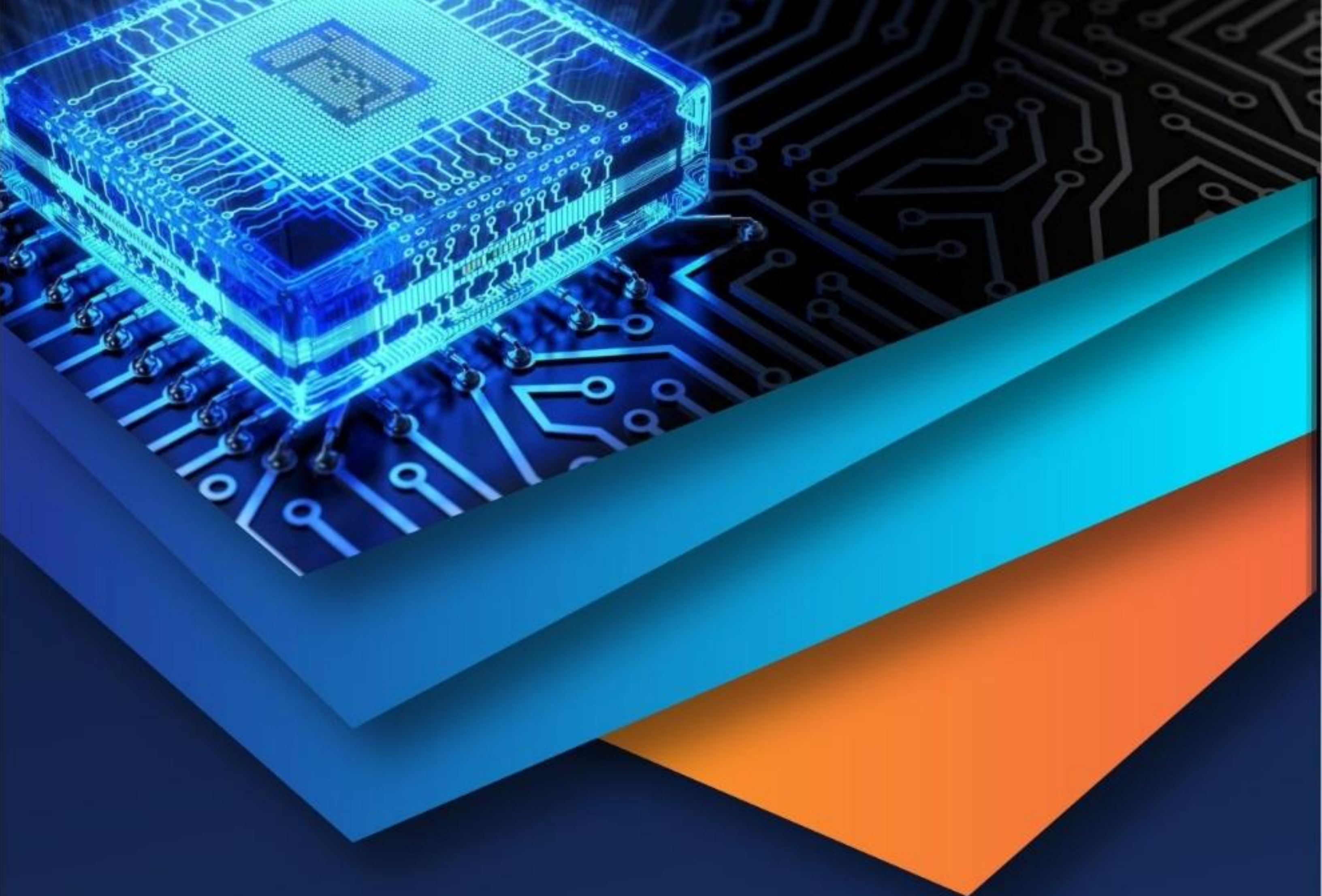

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