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Finite Element Formulation for Prediction of Over-speed and burst-margin limits in Aero-engine disc

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Abstract: Turbo-machinery disks are heavy, highly stressed components used in gas turbine mainly due to over speed and operating temperatures. The experimental burst test is always time consuming and very expensive. Hence the objective this work was to develop finite element (FE) prediction to find over-speed and burst-margin limits. The FE method for the thermal and mechanical analysis is used for the determination of the over-speed and burst margin limit for high-speed aero-engine turbine disc for the speed between 10,000 rpm to 22,000 rpm at variable temperatures. The result shows that the magnitude of the tangential stress components is higher than that of the radial stress components for all the discs under variable temperature distribution. The tangential stress components are higher at inner surface and decreases toward outer surface. The burst margin speed was predicted as per formula and obtained for 18,500, 19,000 and more than 22,000 rpm for thermal + blade load + centrifugal load, thermal + centrifugal load and only centrifugal load respectively.

Index Terms: Gas Turbine Disc, Over-speed, Burst Margin.

I. INTRODUCTION

One of the important safety considerations in aero-engine development is the margin provided on the over-speed and burst-speed capability for all rotating parts, especially for single-stage discs [1]. Excessive disc growth during over-speeding might pass off as a non-event or manifest itself in serious blade rub. A disc burst due to over-speeding and consequent disc-fragment release invariably damages the engine significantly enough to warrant an in-flight engine shut-down [2]. In extreme cases, this event can also result in fatal wreckage of an entire aircraft. Much dreaded titanium fire can also occur, if adequate margin for disc radial / axial growth is not provided.

On the other hand, during design of turbo-engines, regulation rules require to demonstrate a significant reserve factor between operating rotation rate and burst rotation rate of critical parts such as disks. Experimental tests are performed on disks in order to validate this reserve factor. Predictions of this experimental bursting speed could be useful to analyze tests and reduce development time. The most common approach to compute the failure probability involves the first- and second-order reliability methods (FORM/SORM) [3-5], which are respectively based on linear (FORM) and quadratic (SORM) approximations of the limit state surface at a most probable point (MPP) in the standard Gaussian space. Recently, the authors have developed new decomposition methods, which can solve highly nonlinear reliability problems more accurately or more efficiently than FORM/SORM and simulation methods [6,7]. A major advantage of these decomposition methods, so far based on the mean point [8] or MPP [9] of a random input as reference points, over FORM/SORM is that higher-order approximations of performance functions can be achieved using function values alone. In particular, an MPP-based univariate method developed in the authors' previous work involves univariate approximation of the performance function at the MPP, n-point Lagrange interpolation in the rotated Gaussian space, and subsequent Monte Carlo simulation [10]. The present work is motivated by an argument that the MPP-based univariate approximation, if appropriately cast in the rotated Gaussian space, permits an efficient evaluation of the component failure probability by multiple one-dimensional integrations. As per authors none of the analytical work is focused on prediction of over speed and burst margin of aero-engine disc. The burst margin is one of the important components in aero engine design. Hence the objective of the present work was to predict the over speed and burst margin of the aero-engine disc under overloading condition using elasto-plastic analysis in high temperature environment for real component dimensions using FEM and analytical formulae.

II. DEVELOPMENT OF FE MODEL FOR AERO ENGINE DISC

Parametric geometric model of disc is made as per real components as shown in Fig. 1(a) and the same was considered predicting maximum speed and burst margin. The FE model of disc of Fig. 1b consists of 12,534 nodes of PLANE 42 type elements (0.5 mm x 0.5 mm). The mesh consists of 1000-first order elements for one half of the disc thickness.

A rotating hot section component in a turbine engine is in general subjected to a combination of surface loads due to blade pull, centrifugal loads and thermal loads due to varying thermal gradient. The load was determined through FE calculation after defining the axis of symmetry, the rotational speed and the disc and blade material density. In this analysis, the operational turbine speed between 10,000 to 22,000 rpm was applied in incremental load steps. Computations for the rotational speed range of 10,000–22,000 rpm additionally were performed for analysis of phenomena

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occurring in the turbine during excessive speed. The thermal loads at bore temperature of 450 °C and at rim of the disc temperature of 600 °C were considered for analysis as shown in Fig. 1(b). The blade load was distributed on the nodes (load / number of nodes) in the simplified procedure imposed on disc shown in Fig. 1(c).

The turbine disc is considered INCONEL 718 material as per standard discs available in aerospace and the physical properties of the disc material are given in the Table 1.

Table 1: Mechanical and Thermal Properties of INCONEL 718 considered for FE formation for prediction over speed and burst margin.

Property	20	100	400	500	600	700
E, kN/mm^2	20.9	19.6	18.3	17.8	17	15.7
CTE (10^{-6}/°C)	12.2	12.8	13.9	14	14.5	15
K (10^3 W/mm °C)	11.1	12.4	17.9	19.4	21.2	23.1

Axis-symmetric 4-noded PLANE 42 elements, possessing the capability to model plasticity and large strain effects chosen for the analysis [11]. Each node has 2-degrees of freedom, one each in x and y-axis, hence the angular velocity is to be given about y-axis. Arc-length method is made use of

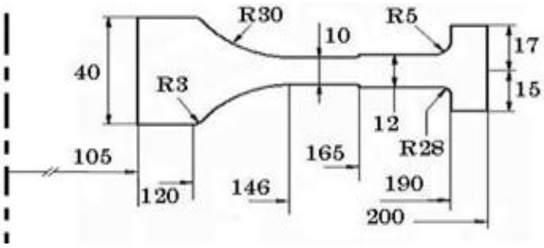

Fig 1a

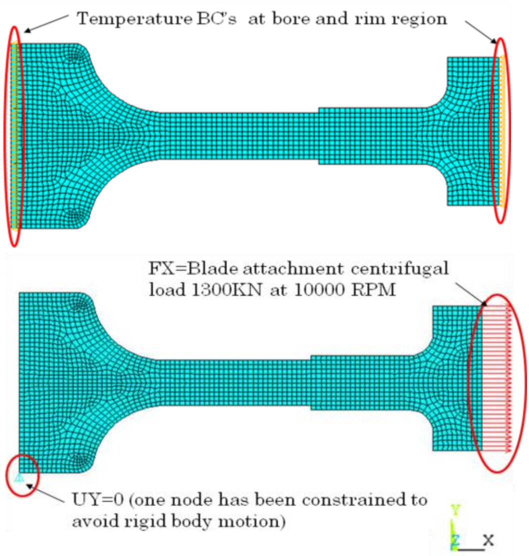

Fig. 1 Sequence of FE model development a) geometrical model, b) thermal constrains & c) loading constrains

and it avoids bifurcation points and track unloading. It causes the Newton-Raphson equilibrium iterations to converge along an arc there by often preventing divergence, even when the slope of the load v/s deflection curve becomes zero or negative. At this stage, it either holds the loading constant or reduces the load increment. Bilinear material properties are considered for varying temperature from bore to rim [12]. Sensitivity analysis is carried out to understand the effect of centrifugal load, thermal load and blade pull in disc individually. The Fig. 2 shows linear stress distribution in the disc.

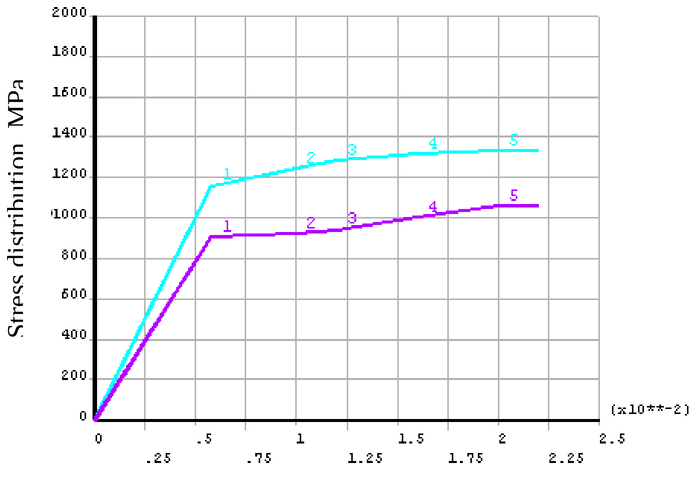

Fig. 2 Bi-linear stress strain curve of the discs materials

III. RESULTS AND DISCUSSION

Case 1: Disc subjected only centrifugal load

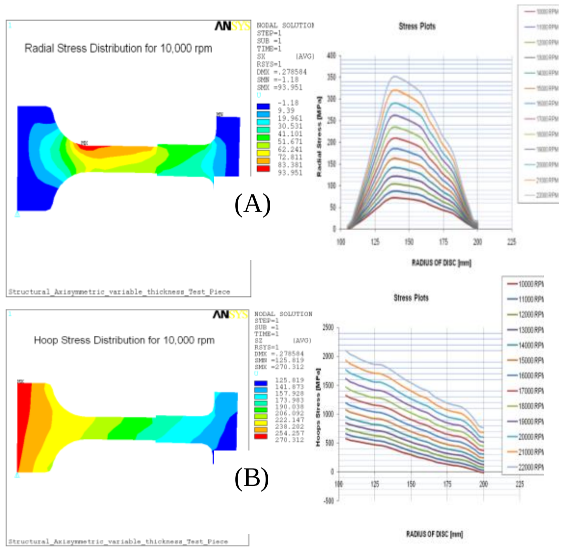

Fig. 3. FE simulation and results of a) radial stress. b) hoop stress distribution in aero-engine disc with centrifugal force only

The Fig. 3 shows the stress distribution in the turbine blade due to centrifugal force from bore of the disc to periphery of disc. Fig 3 (a) indicates both simulation and radial stress distribution in the disc, it is initially increases and reaches peak (around 150 mm) and it decreased towards the outer periphery. Fig. 3 (b) represents the hoop stress distribution in the disc as the function of radius of the disc. It is maximum at inner rim and minimum at outer peripheries.

Fig. 4 shows effect of only centrifugal reaction on stresses and deformation of turbine disc for different speeds. Nature of both stresses is similar for all speeds but stress intensity is increasing with increase speed of the turbine disc.

Case 2: Disc subjected to both and centrifugal load, temperature constraints.

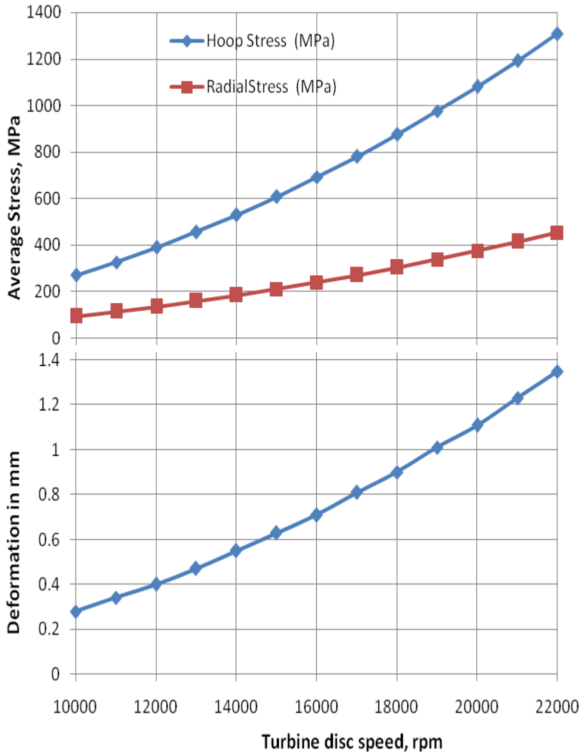

Fig. 4 Effect of turbine disc speed on a) stresses and b) deformation due to only centrifugal Load

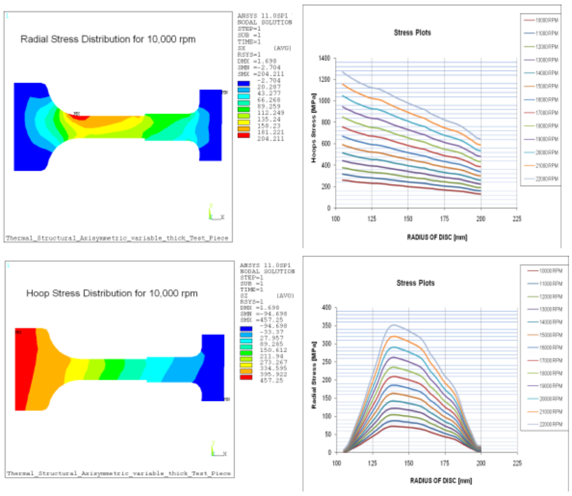

Fig. 5 FE simulation and simulation results of a) radial stress and b) hoop stress distribution in aero-engine disc due to both centrifugal and thermal loads

The Fig. 5 shows the stress distribution in the turbine disc due to centrifugal force and thermal load from bore of the disc to periphery of disc. Even though thermal load influences on turbine stresses the trend of stresses are similar to that of only centrifugal load, but only higher magnitude than the centrifugal loads. Fig. 6 shows both average stress and deformation vs. turbine disc speed. The similar trend can be seen with higher magnitude. Thermal as well as centrifugal loads influence the radial stress of the test disc not balance dimensionally. If you must use mixed units, clearly state the units for each quantity in an equation.

Case 3: Disc subjected to centrifugal load, blade load and temperature gradient tests

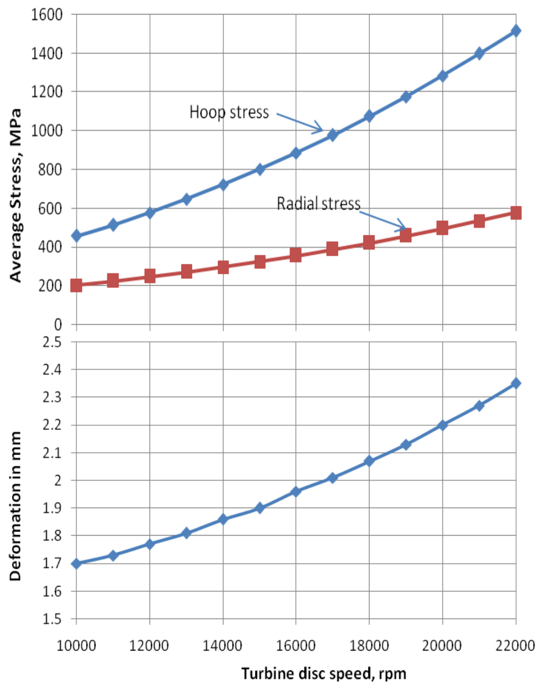

Fig. 6 Effect of turbine disc speed and thermal load (a) stresses and (b) deformation

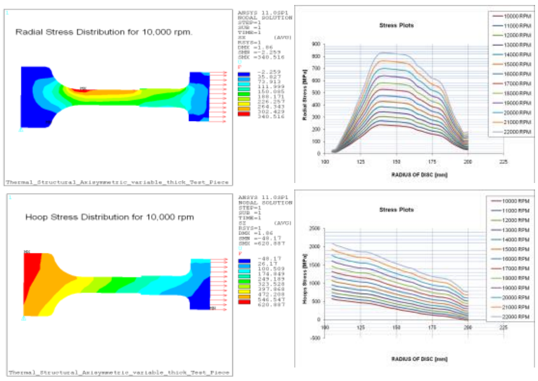

Fig. 7 FE simulation results of a) radial stress and b) hoop stress distribution in aero-engine disc due to blade load, centrifugal load and variable thermal loads

Fig. 7 shows the stress distribution in the turbine blade due to centrifugal force from bore of the disc to periphery of disc for centrifugal, blade and variable thermal loads. Fig. 7(a) indicates the both simulation and predicted radial stress in the disc as a function of radial distance from the disc bore to periphery of disc. The results are similar to previous conditions but only magnitude was changed. Similarly Fig. 7(b) represents the hoop stress distribution in the disc as a function of radial distance. Fig. 8 (a) and Fig 8(b) show the effect of both centrifugal and variable thermal load on stress distribution and disc deformation as a function of turbine speeds.

4.0 Prediction of over speed burst

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The simulation of the experimental test on the burst margin is performed on the disk for all conditions as shown in Fig. 9. Once the stresses are known at each radial station, empirical design criteria may be calculated. Once common design criteria, the burst margin [12] is defined as

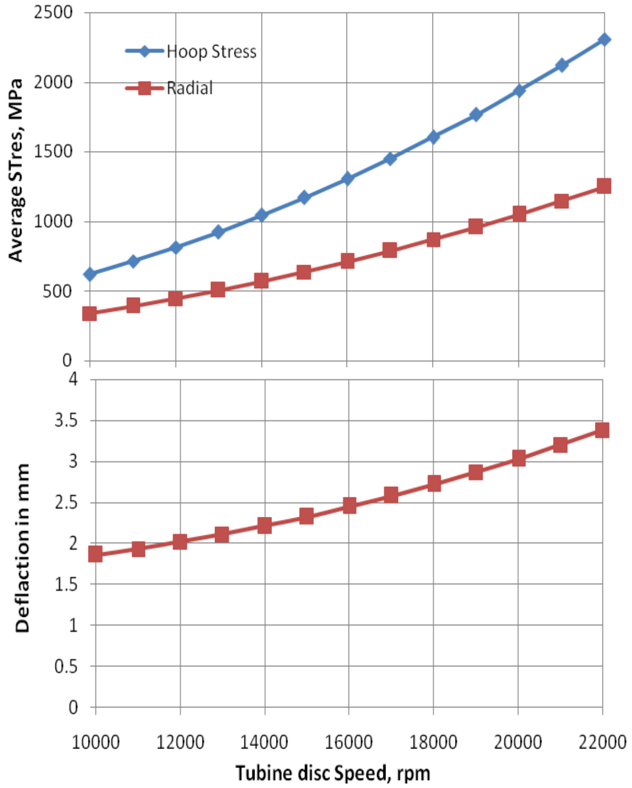

Fig. 8 Effect of turbine disc speed and variable thermal load a) stresses and b) deformation of the disc

$$Burst\ margin = \frac{0.47 \times \sigma_{ult}}{\sigma_{av.hoop}}$$

In this equation the average tangential stress in the disk is related to the ultimate strength of the chosen material. In a disc design the burst margin should always be larger than 1.0. It should be noted that this simple relation assumes that the material has the same ultimate strength at all radial disc. If the disk has a radial thermal gradient this assumption is not true and the burst margin criteria are no longer valid. Regardless, the burst margin still has its uses as an initial feasibility or sanity check of any disk design. In reality, a well designed disk should pass both the burst margin test and the more specific comparison of Von Mises stress vs. material yield strength at each radial station.

The global rotation rate / displacement curves are shown in previous sections for all three conditions as a function of the normalized radial displacement at the rim of the disk and as function of speed. The rotation rate is normalized with respect to the experimental burst rotation rate. One can observe that: (i) the loss of stability of the structure obviously coincide with the limit point of the equilibrium curve as shown in Fig. 9. The disc when subjected to only centrifugal load works safely even rotation of the disc reaches 22,000 rpm but applying thermal load it fails around 19,000 rpm, and in addition to this adding blade load it fails around 18,500 rpm. The analysis, in incremental steps, was further continued until the disc indicated the possibility of bursting. The loading and unloading of the disc due to the speed variation was simulated using appropriate material hardening characteristics, relevant to the operating temperature range.

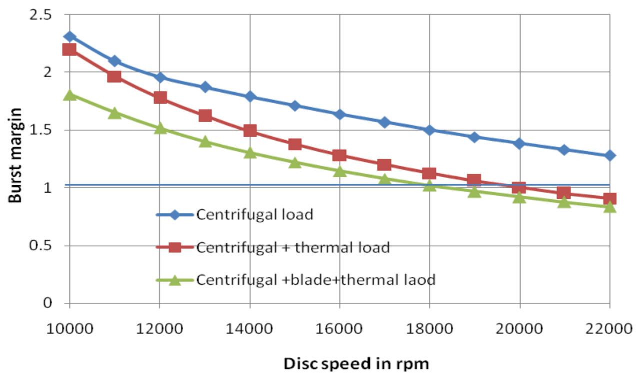

Fig.9. Predicting bursting margin of turbine disc for various disc speed only centrifugal load, both centrifugal load + thermal load, centrifugal + thermal + blade load using FE model.

IV CONCLUSION

In this paper, the authors discussed the application of process modeling to support the fabrication of the critical rotating components required for the gas turbine engine. Main aim of this work was to build FE models of the phenomena occurring during disc failure due to over speed in thermal environment. In the present analysis evaluation of over-speed and burst margins for a gas turbine disc is subjected to combination of thermal, blade and centrifugal loads. It is observed that not only centrifugal load plays a major role but also thermal and blade load dominating on stresses and burst margin of the disc. At the end of the work, the maximum speed limits gas turbine for aero-engine applications are determined. For three high-speed gas turbine disc for the speeds 18,500 rpm, 19,000 rpm and more than 22,000 rpm for thermal+ blade+ centrifugal load, thermal + centrifugal load and centrifugal load respectively for their maximum mechanical powers. However the radial deformation of the disc at burst speed limits tends to be exponential indicating the possibility of burst speed. The study gives an insight understanding the component stresses coming on the rotating disc which are very essential in determining the structural integrity of a gas turbine disc.

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