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The importance of the material properties on the burst speed of turbine disks for aeronautical applications

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ABSTRACT

The computation of the burst of turbine disks for aeronautical engines is a current problem of great practical interest. Turbine disks are stressed by severe loads, for this reason the knowledge of the burst angular velocity is of primary importance for the whole safety of the aircraft during ordinary missions or extra-ordinary conditions that engines may encounter during service.

In this work, a numerical method to predict the burst speed is presented, introducing the physical phenomenon at the base of the burst: the inertial instability. The method is based on Finite Element simulations taking into account the spin-softening effect which leads to instability and therefore to the burst of the disk. Two analytical solutions of rotating structures are used for a preliminary validation of the numerical results that simulate the inertial instability: in both cases the calculated burst speed agrees with the analytical results. The correlation between the nonlinear stress–strain curve and the inertial instability is then addressed by means of simulations that are performed in the end on a real disk subjected to typical loads acting on it. In conclusion, a comparison between the semi-empirical method of Robinson [14], which is at the base of standard disks certifications, and the FE approach is presented in terms of burst speed prediction to show that FE calculation is more accurate to predict the limit speed.

1. Introduction

The turbine disk is one of the most stressed components in an aircraft engine. It works in severe conditions determined by different loads such as centrifugal load, thermal load and blades and slots pulling load. During the years the evaluation of the burst speed has been an issue of great interest mainly for two important reasons: first of all airworthiness requirements impose to prove the disk integrity at some specific speeds through analysis or tests in order to achieve the certification; second the knowledge of the admissible angular velocity determines the shape optimization in terms of weight and dimensions of the disk.

Experimental results show how a disk may burst in different ways: in the "rim peel" burst, a peripheral part is released while the hub section remains intact; in the "hoop mode" burst, the separation occurs along the radial direction and the disk disintegrates in more parts.

Several studies are carried out to investigate the behavior of rotating disks: their aim is the development of analytical methods to calculate stress and strain distributions on the basis of a series of hypotheses in order to simplify the problem and to obtain analytical or semi-analytical formulations of the critical burst speed, such as elastic-perfectly plastic material, plane stress or strain distribution, constant thickness (or with a particular parabolic or exponential law), see Heyman [1], Shikida et al. [2], Genta and Gola [3], Gamer [4], Guven [5], You et al. [6], Callioglu et al. [7], Hojjati and Jafari [8], Aleksandrova [9]. Among papers where analytical results are compared with numerical results obtained by Finite Element Method (FEM) simulations, the study by Maruthi et al. [10] is one of the most recent work that shows in detail the stress distribution in a real disk subjected to loads of different nature using FEM simulations. The work of Vullo and Vivo [11] addresses the problem of a disk of variable thickness and density, subjected either to the centrifugal and thermal load, developing an analytical procedure to evaluate the stress and strain distributions. Hassani et al. [12] used the homotopy method to obtain the mathematical model that describes the disk behavior under thermo-mechanical loads. The results (in terms of stress and strains) have been compared with FEM and RK solutions, showing

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Nomenclature

A	disk cross section
a	disk undeformed inner radius
b	disk undeformed outer radius
r	current radius
r_0	undeformed radius
h	disk thickness
u	radial displacement
ρ	material density
ω	angular velocity
σ_r, σ_c, σ_z	true stress in radial, circumferential and axial direction
ε_r, ε_c, ε_z	true strain in radial, circumferential and axial direction
M	tip mass
m	mass per unit of length
l	beam length
E	Young modulus
v	Poisson modulus
∇	differential operator
$[K]$	stiffness matrix
$[N]$	shape function matrix
q	nodal degree of freedom
p	nodal load
α	thermal expansion coefficient

a good agreement. The study by Maziere et al. [13] presents a method to calculate the burst speed based on the modified global second order work (MSOW), which takes into account the spin-softening second order effect.

With the exception of the latter work, none of the previous mentioned studies consider the spin-softening effect: it causes an increase of the centrifugal force because of the radial deformations, until the whole rotating structure becomes unstable and bursts, in some cases well before reaching the ultimate stress.

In the works by Holms and Jenkins [15] and by Holms and Repko [16] a correlation between the burst strength and the ductility of the disk material is found. In these two last works some experimental results are presented in order to show how the disk burst occurs. The problem of the bursting disks related to the inertial instability when the values of the stress distribution are above the yield limit is also addressed by Weiss and Prager [17]: in this work an analytical approach is presented to evaluate the evolution of strains and stresses, following the stress–strain curve until the process of deformation becomes unstable, using Tresca criterion and its flow rule. Then in the work by Percy and Mellor [18], two theories (Tresca yield criterion and Hencky deformation theory of plasticity) are used to analyze the stress and strain distribution in the instability condition showing that the Hencky theory is more consistent with the physical phenomenon. On the base of experimental results, Percy et al. [19] presented the behavior of disks in terms of deformations when instability and burst occur. The study by Tvergaard [20] focuses on the mechanism of disk bursting analyzing the possibility of bifurcation away from axisymmetric state.

The study by Brunelle [21] is an important work that shows the phenomenon of inertial elastic instability: it addresses the problem showing some analytical solutions about rotating structures with linear elastic behavior. The work made by Tutuncu [22] presents the correlation between the instability of rotating disks and the disk dimensions, anisotropy and Poisson's modulus. In these two papers a comparison is presented between displacements and stresses obtained with classical approach (without taking into account the deformed geometry under loadings) and with an update to the actual dimensions.

Recently the effect of an updated deformed geometry on the stress distribution of the disk has been analyzed by Ekhteraei-Toussi and RezaeiFarimani [23], using a semi-analytical method that takes into account different material behaviors (by means of the Ramberg–Osgood model to define the stress–strain curve) related to different disk shapes. Also Hu [24] developed a mathematical model that considers the effect of radial deformation on disk stress with the increasing of the angular speed. The numerical solutions that are obtained (using an ODE solver), in terms of burst speed, confirm that the disk burst is strongly related to the disk size and to the stress–strain material curve.

The present work focuses on the computation of the burst speed using a FEM analysis carried out by Ansys software; in fact, the FE approach is the most suitable method to understand the evolution of the stress distribution in turbine disks before the inertial instability occurs due to the spin-softening and its importance in the determination of the disk burst (discussed in the previous references) in a real-like turbine disk geometry. In detail, the angular velocity is applied according to a ramp that gradually increases, static equilibrium is calculated for each step and the last equilibrium state allowed by the current load conditions is associated to a limit speed (the burst speed). It is found that the values of the stress distribution corresponding to the last equilibrium state might be smaller than the ultimate tensile stress. The critical speed causing the instability produces a stress distribution along the disk radius whose values lie between the yield point and the ultimate tensile stress or, in other words, the instability takes place when all the different parts of the disks are stressed in the plastic field of the stress–strain curve of the material where a sharp decrease of the Young's modulus is observed, thus causing higher deformations.

A preliminary comparison between analytical results, provided by the Brunelle's study, and numerical results by FEM is shown to validate the capability of the numerical model to simulate the inertial instability. Then, the correlation between the nonlinear stress–strain curve and the inertial instability (and therefore the burst speed computed by FEM simulation) is introduced and addressed highlighting the important role of some parameters such as yield point, ultimate stress, conventional elongation at rupture. The numerical procedure can explain the experimental results presented in Hassani et al. [12], Maziere et al. [13] and Holms and Repko [16]. In conclusion, a comparison between the semi-empirical method of Robinson, widely used to predict burst speed, and the more accurate FEM is presented.

With respect to previous works, this paper confirms the strong impact that the stress–strain curve has on the inertial instability that is the physical phenomenon at the base of disk burst. Moreover, FE method is found to be a suitable tool to simulate the mechanical behavior of rotating disks and a design criterion is proposed to set the limit at which the inertial instability occurs.

2. Problem formulation

A brief description of the mathematical models on which the analysis of rotating disks is based is presented here. Assuming the axisymmetric hypothesis of the disk, the stress and strain components do not depend on the angular coordinate ϑ. The axial stress σ_a will be assumed to be zero for the thin disks here considered