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Evaluation of thermal management strategy based on zoning of stress states of a gas turbine disk

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ABSTRACT

Considering that either passive thermal management from thermal protection or active thermal management from thermal loading reorganization is determined by thermal management strategy, this paper proposes an evaluation method based on the zoning of the stress states of a disk for different thermal management strategies to assess the advantages and disadvantages of different thermal loading combinations or distributions at the initial design stage. The theoretical model for thermal management strategies is first established by abstracting the combination of thermal loading parameters (Q_e, Q_{in} and $\bar{h}$). Subsequently, the zoning principles are defined based on the stress state characteristics. The sensitivity factors $S_{\sigma,in}$ and $S_{\sigma,e}$ are introduced to quantify the variation degrees of the thermal loading parameters Q_{in} and Q_e for stress state. A rotating turbine disk with a nearly real geometry is used as evaluation object to investigate the effects of different thermal management strategies from three aspects: the position of maximum stress, the iso-surface of the maximum stress level and the variation profile of the disk. Results show that the stress states for each thermal management strategy can be divided into four zones based on the position of the maximum von-Mises stress and the direction of the circumferential stress. A three-dimensional space region partition is generated for each stress state, which shows that the appropriate thermal loading combinations in the design are limited and have an application scope. Generally, the thermal loading combinations in the Domain 1(I) zone represent the most appropriate objects in the design process, whereas the other zones should be avoided because of the enormous negative temperature gradient they produce in the disk. Moreover, the values of sensitivity factors $S_{\sigma,in}$ and $S_{\sigma,e}$ in the considered disk profiles are similar, and the effects of the variations in the thermal loading parameters Q_{in} and Q_e on the maximum stress are not influenced by the disk profile.

1. Introduction

As a core part of a gas turbine, a turbine disk operates under severe and complex conditions of thermal loading [1]. As a result, a progressive material deterioration is generated from the accumulation of fatigue and thermal creep damage [2,3], and the safety of the gas turbine is consequently jeopardized.

In general, cooling technologies are used to control the thermal loading of the disk, and the controlled objects can be characterised by temperature level and gradient. Because these two targets are determined by the thermal loading distribution of the disk [4], in terms of physical mechanism, the essence of using a cooling technology is a process of thermal management of the turbine system. The purpose of the development of cooling technology is to carry out a different thermal management strategies. Here, for a thermal management strategy, the positions of the heat sources and the organization of the cooling flow are the concrete implementation methods for the disk cavity. The temperature level and gradient of the disk is a reflected phenomenon, and the stress level and distribution of the disk are the acquired results or assessment criteria to guarantee the permissible strength of the disk. According to the types of thermal loading distribution, a proposed thermal management process can be classified as passive or active thermal management.

1.1. Passive thermal management for a turbine disk

From the perspective of thermal protection, in the last four decades, most of the studies in the field of turbine systems have concentrated on the enhancement of cooling efficiency under conditions of limited cooling air consumption [5–7], because cooling technology is restricted by the amount of cooling air from the compressor and excessive consumption of cooling air will directly cause a decline in the efficiency

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Nomenclature

E	Young's modulus of elasticity
F	Radial force
h	Convective heat transfer coefficient
$\bar{h}$	Average convective heat transfer coefficient
I_n	n-Order Bessel function of the first kind
k	Coefficient of the thickness function
K_n	n-Order Bessel function of the second kind
n	Number of annular disks
Q_e	Heat energy on the outer surface of the disk
Q_{in}	Heat energy on the inner surface of the disk
r	Radius
r_1, r_2	Geometrical sizes of the disk
$[R_{D_{1,2}}]$	Coefficient matrix of Eq. (1)
$[R_F]$	Coefficient matrix of Eq. (1)
$[R_Q]$	Coefficient matrix of Eq. (1)
$[R_T]$	Coefficient matrix of Eq. (1)
$[R_V]$	Coefficient matrix of Eq. (1)
S_σ	Sensitivity factor, $S_\sigma = \partial\sigma_{e\text{-maximum}}/\partial Q$
t	Disk temperature
t_{ref}	Reference temperature
W	Substitution variable $W = (\bar{h}/\lambda\delta)^{0.5}$
α	Coefficient of thermal expansion
δ	Width of the disk, $\delta = Cr^k$
λ	Heat conductivity of the disk
λ_{air}	Heat conductivity of air
μ	Poisson's ratio
μ'	Dynamic viscosity of air
ρ	Disk density
ρ'	Air density
σ_r	Radial stress
σ_θ	Circumferential stress
σ_e	Equivalent stress (von-Mises)
ω	Angular velocity of the rotating disk

Superscripts

(i)	i-th annual element

Subscripts

maximum	Maximum
e	Outer radius
in	Inner radius

of the gas turbine.

For cooling method, the impinging jet cooling is extensively used as a cooling method for rotating disks because the interaction between the rotating disk and impinging jet allows for a significant heat transfer improvement [8]. To help understand this complex phenomenon and reveal the mechanism of the flow and heat transfer between the rotating disk and the impinging jet, numerous studies [8] have been conducted to study simple and complex rotor–stator geometries, particularly the superposition of separate effects, such as rotation, impingement with different angles of attack, flow regime and wall temperature profile. In addition, single and multiple impinging jets for rotor–stator systems have also been investigated. Generally, the results of these studies show that the flow regimes depending on the height of the gap between the rotor and stator, through flow velocity and rotational speed can clarify the complex fluid flow and heat transfer in the gap. A review of the latest achievements in this field was written by Harmand [8].

These studies support that the cooling structure for a typical disk cavity has evolved from a centric air inflow configuration to a pre-whirl inlet configuration [9–11]. Some novel disk configurations for the turbine disk have also been proposed, such as the twin-web disk [12–14]. However, these thermal protection-based cooling technologies do not change the type of thermal loading distribution, in which the temperature gradually decreases from the outer surface to the inner surface of the disk. Thus, this process of thermal management based on thermal protection can be classified as passive thermal management and is implemented by a passive thermal management strategy.

1.2. Active thermal management for a turbine disk

Nevertheless, the potential of thermal protection in pure cooling technologies to guarantee sufficient disk strength have been nearly

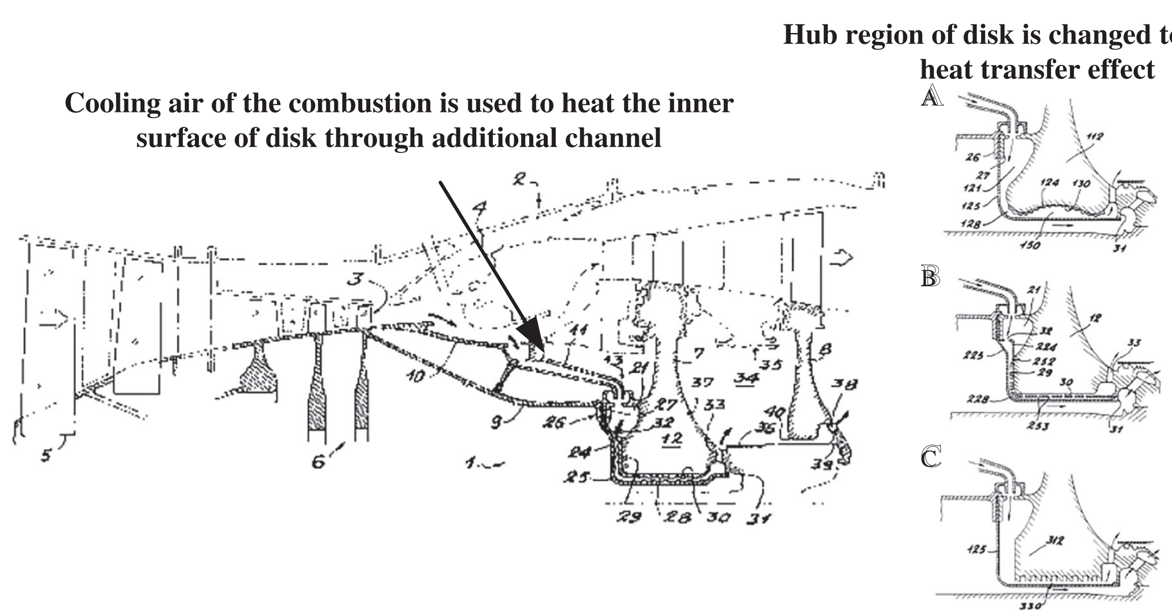

Fig. 1. Schematic diagram of the turbine system in SNECMA [15].