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Effect of actively managed thermal-loading in optimal design of an aeroengine turbine disk

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ABSTRACT

The effect of actively managed thermal loading for optimal design of turbine disk was investigated to seek the better balance between strength demand and minimum weight/volume. An integrated process of design was developed to achieve automatic iteration for this multi-objective optimization problem. Under equal consumption of heating energy and cooling air conditions, two types of actively managed thermal loading with different allocation ratios of heating energy ($\phi = 0.1$ and $\phi = 0.2$) in the outer and inner surface of disk were considered in the process of optimization. As a comparison, the disk at conventional thermal loading conditions ($\phi = 0$) was also optimized at the same design conditions. Results showed that the better structure of disk with smaller weight/volume and lower maximum stress level was obtained due to thermal loading management. Through actively managing the thermal loading to reorganize the temperature distribution of disk, the optimized weight/volume and maximum hub stress fallen 2.24% and 12.16% respectively to compare with the conventional thermal loading condition. The reason for the preceding effect could be explained that an artificial V-shaped temperature distribution was built in the disk through actively managing thermal loading, and correspondingly, the reverse temperature gradient between hub and web produced a pulling effect and counteracted parts of stress from rotating.
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1. Introduction

As one of the core parts of gas turbine engines, turbine disk operates under the extremely severe and complex conditions of thermal loading [1]. The result is that a progressive deterioration of material is generated due to the accumulation of fatigue and thermal creep damage [2–3] and consequently jeopardizes the safety of the gas turbine.

In general, several cooling technologies are developed on the turbine disk in order to decrease the thermal loading. The average temperature $\overline{T}$ and temperature gradient of disk are used to evaluate the performance of the cooling method [4]. However, cooling technology is restricted by the amount of cooling air from the compressor. And the excessive consumption of cooling air will directly cause the efficiency of the gas turbine to decline. Thus, in the last four decades, most of the studies in the field of disk cooling technology primarily concentrated on the cooling structure to enhance the cooling efficiency under the limited cooling air consumption condition [5–7]. For disk cavity [8–10], the typical cooling structure includes centric air inflow configuration, high positioned air inflow configuration, and pre-whirl inlet configuration et al. For disks, some novel disk configurations are developed, i.e., Twin web disk [11–13], which has a high cooling efficiency because the air enters the inside of the disk directly.

Nevertheless, the potential of using pure cooling technology to ameliorate thermal loading has been nearly exhausted. Thus, the current development trend is hope to find breakthrough from new materials [14–17], i.e., functionally graded materials (FGMs), super alloy materials, et al. However, these new materials may inevitably bring complication in manufacturing and still require many years to develop to be used in disk.

All the research work mentioned above has shown lots of effort to ameliorate thermal loading or enhance the material property to resist the damage from thermal loading. However, it should be noted that the essential of using cooling technology or using new material is to guarantee the permissible strength of disk in harsh working environment. But using cooling technology and new material are not the only two ways to guarantee the strength demand of disk. That is, it is possible that the strength demand of disk can be more easily satisfied by actively reorganizing and managing the thermal loading under existing cooling technology and material conditions.

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Nomenclature

A	area of outer surface for single blade
c	coefficients of $\delta(r) = c(r/r_r)^k$
$C_{1,2}$	coefficients of temperature equation
C_3	substitution variable
k	coefficients of $\delta(r) = c(r/r_r)^k$
E	Young's modulus of elasticity
F	tensile force from rotating blade
$\overline{h}$	average convective heat transfer coefficient
I_n	n — order Bessel function
K_n	n — order Bessel function
m	mass flow
m_{blade}	mass of single blade
n	the number of blade for whole disk
P	pressure loading from rotating blade in outer surface of disk
q	heat flux
Q	heating energy
$\tilde{Q}$	dimensionless heating energy
r	radius
W	substitution variable $W = (\overline{h}/\lambda\delta)^{0.5}$
α	coefficient of thermal expansion
δ	width of disk
ϕ	allocation ratios of heating energy
$\tilde{\phi}$	ratio of heating flux
λ	heat conductivity
μ	Poisson's ratio
ρ	density of disk
σ	radial stress
σ_θ	circumferential stress
σ_e	equivalent stress
$\sigma_{hub\text{-maximum}}$	maximum of von-Mises stress of hub
ω	angular velocity of rotating disk
r_h	inner radius of disk in optimal design
r_r	outer radius of disk in optimal design
Z_h	half-width of hub
Z_r	half-width of rim
L_h	thickness of hub
L_r	thickness of rim
L_w	simplified of transition between rim and web
$\delta(r)$	variation half-width of web $\delta(r) = c(r/r_r)^k$
l_1, l_2, l_3, r_l	Main geometric sizes of disk cavity
V	volume
X	value of the design variable

Subscripts

blade	blade
e	outer surface
i	inner surface
in	inlet of disk cavity
out	outlet of disk cavity
cooling	cooling air
total	the sum of thermal stress and centrifugal stress
n	the n-th design variables, $n = 1,2,3\ldots$
n-min	minimum value of the i-th design variables

Starting from the concept, as shown in Fig. 1, an active control thermal loading method to ameliorate stress in aeroengine turbine disk was proposed by Ding and Li on uniform thickness rotating disk [18]. The hub of the disk was actively heated to achieve energy redistribution and analogous V-shaped temperature distribution of disk. Then, the pulling effect from active produced reverse temperature gradient could counteract the thermal stress caused by positive temperature gradient and parts of stress from centrifugal force, enabling the stress level of disk to be declined. Thus, the essence of actively managed thermal loading was to actively control and establish favorable temperature gradient. In this point of view, theoretical and numerical study was carried out as shown in Fig. 2. Then, in Ding and Li's future study [20], an experimental study was performed to validate temperature distribution and circumferential stress level on real turbine disk with actively managed thermal loading method under near-vacuum environment and rotating condition. Results obtained the same stress control effect with theoretical and simulation analysis. As shown in Fig. 3, by actively enhancing the temperature of lower part of disk to reorganize thermal loading, the decline ratio of maximum circumferential stress level in hub could be arrived 28.66% to compare with conventional thermal loading condition even in 6000 rpm.

In the above-mentioned researches, although the obvious effect of stress decline is obtained, however, it should be pointed out that the better performance of the disk is not only associated with the lower stress level. In practical applications, weight is also an important and sensitive role for aeroengine, and the design optimization is to balance the maximum stress level and the minimum weight under an acceptable strength condition of material. Thus, since the stress level of the disk, especially the maximum stress, can be remarkably ameliorated by actively managed thermal loading, the heavy disk designed in a general fashion with the goal of satisfying strength demand may reduce weight under the lower stress level condition. In other words, the better balance between strength demand and minimum weight of disk may be obtained. Currently, however, the research about it has been almost absent in this field.

This paper presents optimization analyses for disk profile design to investigate the effect of actively managed thermal loading. Using the same thermal management method proposed in Ding and Li's study (as shown in Fig. 1) [18] and validated in experiment [20], the temperature of lower part of disk is actively enhanced by directly heating the inner surface of disk to achieve the thermal loading reorganized. Here, it should be pointed out that, in study, the thermal loading can be reflected by the temperature distribution of the disk, and the stress level and weight/volume are considered to evaluate the optimal structure. Therefore, the objective of this study is to investigate the variations of balance between stress level and minimum weight/volume for different optimal structures caused by changed temperature distribution of the disk, which is determined by actively reorganized thermal loading. The revealed relevance between optimal structure and thermal loading from analysis results will be helpful to provide another insight to obtain better balance between strength demand and weight/volume in the disk design process.

2. Optimization problem

2.1. Model of turbine system

A typical rotating disk system with disk cavity is given as shown in Fig. 4(a) and this simplified disk is considered for profile optimization. In analysis, the disk body material is assumed to be isotropic and homogeneous and the geometry parameters can best be represented in the symmetric section on the (r, z) plane using a cylindrical coordinate system [21]. Additionally, because this study is focused on the influence of thermal loading, the external (blades) loading and the body forces are not be taken into account in the profile optimization to reduce the complexity of analysis. Moreover, to further reduce calculation costs, the design variables are simplified to consider the web profile of disk $\delta(r) = c(r/r_r)^k$ only, and the hub thickness L_h is changed correspondingly. That is, as shown in Fig. 4(a), point A of web profile is fixed but point B has a degree of freedom in the radial direction. Simultaneously, the

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