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An equilibrium multi-objective optimum design for non-circular clearance hole of disk with discrete variables

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Abstract An Equilibrium Multi-objective Optimization Model (EMOM) with self-regulated weighting factors has been proposed for the optimum design of non-circular clearance hole on the front flange of turbine disk. In the "equilibrium design", both the stress decrease around the hole and the least hole's profile variation are considered, which balances two ambivalent design goals. Specific discrete variables are applied to realize the standardization design in the optimization process, in which a Surrogate Genetic Coding Algorithm (SGCA) is introduced, and a special check module is used to get rid of repeated fitness evaluation of the samples. The method offers an equilibrium design for the non-circular clearance hole of the turbine disk with great accuracy and efficiency.

1. Introduction

The turbine disk of aircraft engine rotates at very high speed and under high temperature, which usually results in severe stress situations, especially on the region near the holes. Lots of practical and theoretical researches have shown that the failure of disks caused by stress concentration is one of the most major reasons for the reduction of its service life.[1,2]

One effective way to lessen stress concentration is to use non-circular hole instead of circular one, which has already been applied to the turbine disk of CFM56-III, see Fig. 1.[3] In Fig. 1, 1 in = 25.4 mm. In Ref. 4, a geometrical model for the non-circular hole was given by Chen et al. and an optimization model was proposed too.[4] It can also be seen from Fig. 1 that the non-circular hole is biaxial symmetrical. The profile consists of 8 arcs, ie. main arcs (R_1) and transition arcs (R_2). However, further researches show that the maximum stress around the hole will decrease monotonically when the upper bound of the radius of the main arc increases, which means the profile of the hole tends to be a "square" and that is not a good option in most cases.[5,6] To introduce balanced design

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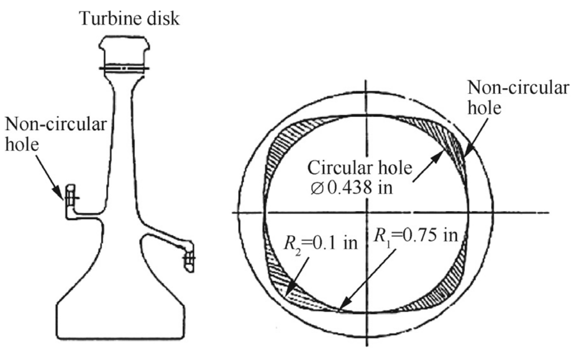


Fig. 1 Non-circular clearance hole on turbine disk.

ideas into the optimization is an effective way to solve this problem.

The turbine shaft, labyrinth disk and turbine disk are connected by 48 long-bolts and nuts. Fig. 2(a) shows 1/48 sector model of the disks. The bolt joints of turbine components are illustrated in Fig. 2(b). The turbine shaft and turbine disk connected with bolts have similar local connecting structures and rotate at the same speed. According to the widely accepted equal-life design criteria, to design two connected components with similar service life or similar stress level might be a better choice. Such balanced designed structure can effectively avoid over-designs and features better economy.[7] Take the turbine components of CFM56-III for example, the stress levels around the clearance holes of the turbine shaft and turbine disk are designed to be with almost the same value, which should have adhered to the equal-life design principle. This may offer a reference for the optimization of non-circular clearance holes on turbine disks.

Less profile variation of the clearance hole for the turbine disk will offer larger contact area for the plate nuts; see Fig. 2(b). The contact condition between bolt and the hole will not be deteriorated. On the other hand, a relative "conservative" option (less profile variation of the hole) will lead to a "confident" design, and will be benefit to the processing, testing and assembling. Therefore, a compromise design is needed. The stress reduction and the least profile variation can be considered concurrently.

In order to guarantee machining precision, the dimensions of the non-circular hole should be rounded to meet the requirements of industry specification. This means the profile of non-circular hole will be optimized as the one with specified dimensions, rather than that with casual discrete ones.[8] So far, several optimization methods were already used in dealing with discrete variables, such as Brand-and-Bound,[9] simulated annealing algorithm,[10] harmony search,[11] Genetic Algorithms (GA),[12] ant colony algorithm[13] and some other nature-inspired methods.[14] Yet variables discretization processing are still tedious and inaccurate, and rounding design variables of new design to allowable dimensions usually needs an overcomplicated algorithm.[15–17] Moreover, there always lacks an effective way to expurgate the unreasonable samples produced in those algorithms.[18]

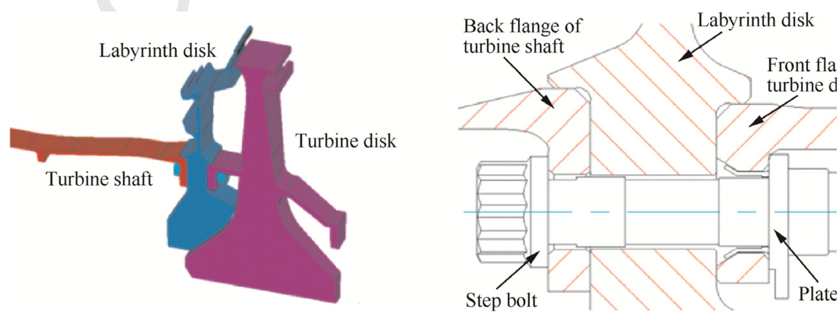
In this paper, we introduced an Equilibrium Multi-objective Optimum Model (EMOM), in which balanced design ideas are proposed, for a compromise design between the stress reduction and the least profile variation of the hole on the turbine disk. Also, the dimensions of the non-circular hole are selected as a group of discrete variables to meet the industry specification, and a Surrogate Genetic Coding Algorithm (SGCA) is proposed to solve the non-circular-hole optimization problems. In this study, an indirect coding method and a check model are also applied to check the feasibility and eliminate redundant fitness evaluations.

2. Construction of equilibrium multi-objective optimum model

2.1. Structural analysis of turbine disk based on FEM

The loads acted on the clearance hole of the front flange of the turbine disk are quite complicated. Actually, the centrifugal load, torque, interference fit, pretension of the bolt, axial load and thermal load can be the candidates which affect the stress conditions of the hole. Among them, the centrifugal load is the major load which dominates the stress level of the hole. To build a feasible and efficient optimization model, the complex loads could be reasonably predigested and the factors that have less influences on the stress of the hole could be ignored temporarily. As discussed in Refs. 4 and 6, a simplified mechanical model has been proposed and only centrifugal load were considered. Researches have shown that the non-circular hole optimized with such simplified model still has the best performance when complicated load conditions of the turbine disk are considered.[5]

The Finite Element Model (FEM) for the optimization model of the turbine disk is shown in Fig. 3. The material of the turbine disk is Ni-based high temperature alloy GH4169. The rotation speed is $\omega_{\max}$ = 14,731 r/min and the working



(a) Turbine components (b) Bolt joints of turbine components

Fig. 2 Turbine components.