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轮盘剖面形状的优化设计

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摘　　要

本文提出一种实用的轮盘优化模型，它可用中心孔半径、轮毂轴向厚度和外半径、轮颈半径以及轮毂、轮缘与轮辐转接处的转接角等几何参数来描述，整个轮盘可近似为由一系列不等轴向厚度的圆环组成。一个能自动生成计算截面的子程序，响应上述诸参数的变化，灵活地生成任意个径向厚度各异的不等轴向厚度的小圆环，以这些小圆环的轴向厚度和上述诸几何参数为设计变量，以轮盘设计的五个应力准则为约束条件，以轮盘重量为目标函数，采用随机射线法+随机投点法的组合优化方法，加速收敛，达到轮盘重量最轻，剖面形状最优。

一、前　　言

轮盘重量最轻和剖面几何形状最优是轮盘优化设计中既一致、又有区别的重要目标。早先，文献[1]所得到的优化轮盘的剖面外形为双曲线，而文献[2]为5次幂多项式，文献[3]则简单规定为一条直线和两个圆弧。尽管所考虑的载荷和约束条件不同，但上述优化轮盘的剖面形状与使用中的轮盘差别很大，在工程设计中未见实际应用。

一种将轮盘近似为若干圆环，圆环的优化厚度用数学规划确定，最优轮盘的剖面形状由台阶修圆后得到的做法，已被一些学者所采纳[4, 5]。

本文提出，选择若干主要几何参数来描述传统盘型（如图1），以这些几何参数和上述诸圆环的轴向厚度为设计变量，以轮盘设计的五个应力准则[6]为约束条件，以轮盘的重量为目标函数，在自动生成计算截面的前提下，采用随机射线法+随机投点法组合优化方法（参见图3），在一定的寻优时间内可得到最轻轮盘的最优剖面形状。

二、简化模型与自动生成计算截面

如图1所示，以若干直线段来近似表示轴对称的轮盘剖面外形曲线，每一直线段划分出一个梯形，引入加权因子C，用以确定自动生成若干小梯形时，小梯形高度的大小。若C＞1，小梯形高度渐增；若C＜1，小梯形高度渐减；若C＝1，高度相等，即等分。由图2可见，生成点的坐标可由下式[5, 7]计算：

$$r_i=(r_b-r_a)\left(\sum_{j=1}^{i}C^{j-1}\Big/\sum_{j=1}^{n}C^{j-1}\right)+r_a$$

$$h_i=(h_b-h_a)\left(\sum_{j=1}^{i}C^{j-1}\Big/\sum_{j=1}^{n}C^{j-1}\right)+h_a$$

值得指出，这种方法具有普遍意义，各计算截面上的温度t、弹性模量E、线膨胀系数α，屈服极限$\sigma_{0.2}$等，均可同理生成。当轮盘中心孔半径r_0、轮毂外半径R_1及其轴向厚度

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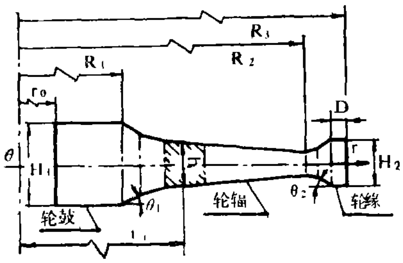

图 1 轮盘简化模型及其几何参数
r_0.中心孔半径 R_1.轮毂外半径 R_2.轮颈半径
R_3.轮缘半径 H_1.轮毂轴向度 H_2.轮缘宽度
D.轮毂深度

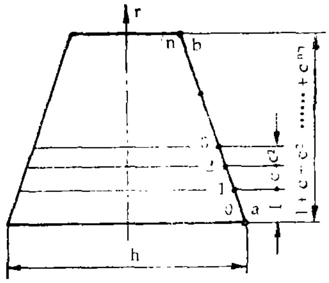

图 2 自动生成计算截面的原理

H_1、轮颈半径R_2与转接角θ_1、θ_2作为设计变量时，自动生成计算截面子程序能自动响应这些设计变量的变化，生成新的初始点。

三、优 化 策 略

根据图 1 所示的轮盘简化模型，除轮缘宽度H_2由叶片/轮盘连接的要求优化确定外，其余几何参数和一系列不等轴向厚度圆环的厚度h_i均作为设计变量，在优化后确定数值大小。

1. **问题的数学规划表示** 设轮盘由K个不等轴向厚度的圆环组成，其厚度h_i（i＝1，2，…K）为设计变量，r为材料重度，轮盘重量W为目标函数，即

$$\min W=\min \pi\gamma\sum_{i=1}^{k}(r_{i+1}^2-r_i^2)\ h_i$$

应满足的轮盘设计五个应力准则为[6]：

（1）最大离心径向应力不超过0.2%屈服极限的75%，即 $(\sigma_{r,\max}/0.75\sigma_{0.2})-1\leqq 0$.

（2）平均周向应力不超过0.2%屈服极限的75%，即 $(\sigma_{T,CP}/0.75\sigma_{0.2})-1\leqq 0$.

（3）内径处的周向应力不超过0.2%屈服极限的95%，即 $(\sigma_{T,O}/0.95\sigma_{0.2})-1\leqq 0$.

（4）轮辐的周向应力不超过0.2%屈服极限的85%，即 $(\sigma_{T,辐}/0.85\sigma_{0.2})-1\leqq 0$.

（5）总安全储备：$1-$（计算安全系数SK_i/要求安全系数SK_i）$\leqq 0$，（i＝1，2，…，K。）

2. **优化方法及其逻辑框图** 本文在文献[5]的基础上，改善轮盘简化模型，将轮盘剖面的几个主要几何参数H_1，R_1，r_0，R_2、Q_1、Q_2增加为设计变量，并直接取值于随机投点的随机数，经转换为对应处的圆环轴向厚度大小后，使当前轮盘剖面外形有关直线段的始末点发生变化，自动生成计算截面的子程序自动响应这种变化，生成相应的计算截面，在满足轮盘设计五个应力准则[6]的约束条件下，由随机射线法直接确定各不等轴向厚度圆环的厚度h_i。在这里，随机投点法通过自动生成计算截面子程序，为随机射线法提供可改变的初始点；而随机射线法又为随机投点法提供好点，在好点的基础上再随机投点，从而加速了收

敛速度，这种优化方法，是随机射线法与随机投点法的交互式组合，简称为随机射线法＋随机投点法的组合优化方法。这种优化方法的逻辑框图见图 3 。

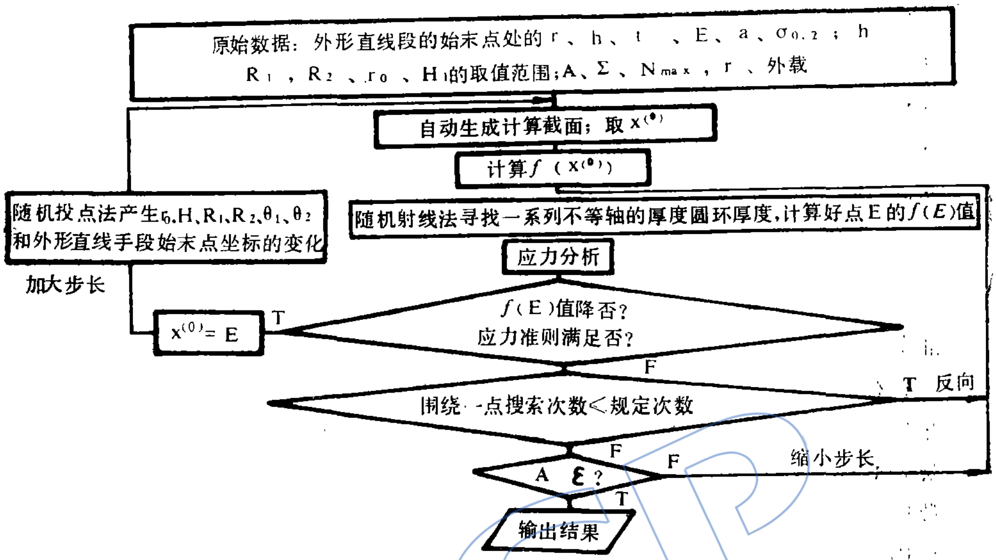

图 3　优化逻辑框图

四、算　　例

初始点选自某高压涡轮盘的几何尺寸数据，按组合优化程序(图 3)，在微机IBM-PC 上运行，平均 5 ～ 7 分钟寻得一个可行点，现选出 5 个与初始点比较，列于表 1 。可见最优点应为 5 号盘。

轮盘剖面形状的变化及其对应的应力分布见图 4 。

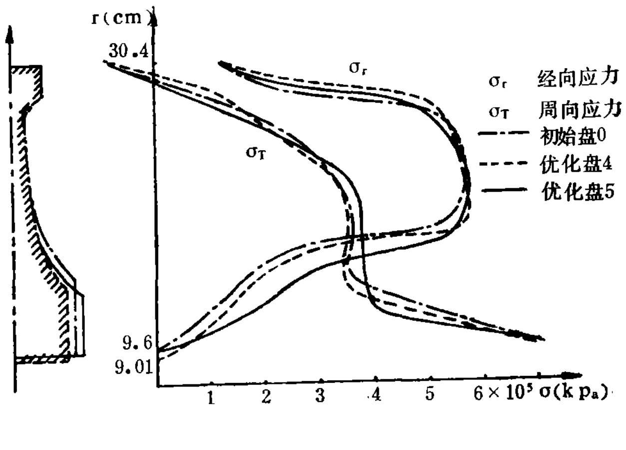

图 4　轮盘剖面形状的变化及其对应的应力分布

表1 优化设计计算结果

参数 / 盘号	r_e (cm)	H_1 (cm)	R_1 (cm)	R_2 (cm)	θ_1 (0) 度	θ_2 (0) 度	轮辐平均周向应力 (KPa)	轮盘剖面面积 (cm^2)	轮 盘 重 量 (N)
0 (初始)	9.6	8.6	12.35	28.5	40.023	40.468	412111.91	46.305	805.439
1	8.87	7.8	11.92	28.5	58.676	34.856	404351.71	43.778	734.577
2	9.63	7.8	12.09	28.5	37.664	34.882	401373.33	44.013	732.969
3	8.85	7.8	11.52	23.5	37.132	30.785	406143.97	43.447	728.801
4	9.01	7.8	11.36	28.5	44.862	30.745	410586.19	42.867	723.692
5	9.6	8.7	11.63	28.5	36.727	31.596	431477.39	39.113	707.039

五、结　　论

算例证实，本文提出的组合优化方法，是一种同时优化轮盘重量和轮盘剖面形状的有效设计方法，具有实用价值。由上面的分析计算可得如下结论：

1. 在只有一个初始点的情况下，仅以各不等轴向厚度圆环的厚度作为设计变量时，轮盘重量只减轻8.86%[5]。本文提出增加轮盘剖面的几何参数作为设计变量后，又相应增加初始点的数目，使重量减轻12.22%，效果十分明显。

2. 采用多种优化方法（即使是收敛率很低的随机方法）的组合，可以提高收敛速度和优化计算效率。本文提供的组合优化方法在IBM-PC上，平均5—7分钟寻到一个可行点。

3. 由于应力分析采用常规的二次近似法（采取自动生成计算截面措施后，计算精度可以达到理想的程度），是平面应力状态，轮辐没有偏心孔（发动机轮盘需开此类孔），也未考虑断裂力学准则的约束，故只适用于轮盘初始设计的优化，以便为进一步的设计分析提供一个科学的轮盘雏形。

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temperature and to research heating and controlling techniques of temperature field. In this case, the surface of outer edge of the disk is wrapped with heating tape which is a polyester film coated by carbon. The temperatures of the model are measured with thermocouples EA2 embedded in the surface or indepth of the model, and are autocontrolled.

Secondly, the photothermoelastic experiment and theoretical calculation of a plane disk have been carried out. Both results of experiment and calculation are in good agreement. It is proved that the methods and techniques proposed can be usefulfor practice.

Thirdly, the photothermoelasticity model test of a turbine disk has been completed. The data of the test can be used as a reference for turbine disk design.

OPTIMUM DESIGN FOR PROFILE CONTOUR OF TURBINE DISK

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Abstract

A combined optimization method for searching the minimum disk weight and the best disk profile contour is provided which uses the random-walk method and the random-try method alternately. The whole disk profile contour can be linearized by linear segments, and thus the disk can be treated as a series of trapezoid-section ringlets. A subroutine for automatical generation of calculation sections is deveoloped. Taking the disk weight as objective function, the geometric parameters and the axial thickness of the ringlets as design variables, and the five stress criteria as constrains, we applied the combined optimization method to a practical disk and obtained a feasible point within 5—7 minutes on an IBM-PC. After one hour calculation the disk weight has been reduced 12.22%. It is proved that this method increases convergence rate obviously.

HIGH- AND LOW-CYCLE COMBINED FATIGUE AND ITS TEST TECHNIQUE

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Abstract

A simple combined fatigue test facility is introduced, which produces and controls high- and low-frequency combined load spectra by means of a closed circuit consisting of a microcomputer and a hydraulic servo unit. The minor-cycle frequency attains 100Hz with a force amplitude of about 500kg, but higher frequency(say, 400-500Hz) may be attained if a better servo unit be available.
JASP

About 50 specimens of aluminum alloy LY12-CZ have been tested and the results show that both the minor-cycle frequency and force amplitude have a detrimental effect on crack initiation life.

A ratchetting phenomenon appeared as the minor-cycle frequency was lowered to 10Hz. It is probably a "deformation failure" in this case.

A STUDY ON IGNITION OF SOLID PROPELLANT BY CO_2 LASER

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Abstract

Experimental research and theoretical analysis have been carried out by means of a CO_2 laser as the radiation source to heat the test samples at atmospheric pressure and temperature. The ignition delay of each of the test samples was measured as a function of radiation intensity. According to the experimental observation and theoretical analysis, a comprehensive model of ignition for composite solid propellant is established which takes into account the effects of the gas-phase reaction, the oxilizer release, the hetergeneous reaction and the polymer fuel pyrolysis in the depth of the propellant. The results of theoretical analysis come to quite a good agreement with the corresponding experimental data. Both experimental and computational results show that the ignition delay decreases with increasing radiant heat flux. The minimum and the optimum values of heat flux appear to exist. The criterion of ignition is deduced.

AN OPTIMIZATION DESIGN OF ENERGY CHARACTERISTICS OF COMPOSITE SOLID PROPFLLANTS

Tian Deyn and Yang Bin

(National University of Defence Technology)

Abstract

The free energy minimization technique is adopted for calculation of theoretical rocket performance under equilibrium flow conditions. According to optimization theory, the direct search method is employed in combination with a computer program. A composite solid propellant ingredient is chosen for maximum specific impulse and maximum characteristic velocity. The numerical results obtained agree fairly well with the results obtained by graphical method for determining the optimum composition of solid propellant systems.